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ELECTRICAL ENGINEERING

A FIRST YEAR COURSE

BY

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PREFACE

THE work included in this book is about as much as can be taught in the electrical portion of a first year electrical engineering course at an evening technical school. Most students before commencing the study of electrical engineering proper, attend a previous course consisting of classes in mathematics, physics, and chemistry. This may be regarded as a preliminary year. In the first year, such students take mathematics, machine drawing or mechanics, and electrical engineering. On the other hand, some students in the preliminary year learn the subject known as magnetism, and electricity. To such students, the matter dealt with in the first two chapters of this book and some of that in chapters iii. and iv. will be recapitulatory, but it has been thought advisable to include this preliminary work to meet the needs of those not taking regular courses, and also of the private student.

The examples which will be found at the end of each chapter bear almost entirely on the work dealt with in the chapter. A large number of them are taken from the City and Guilds of London Institute's examination papers, those marked (E) from the elementary grade, and those marked (O) from the ordinary grade.

The author is indebted to several firms for the loan of blocks from which some of the illustrations have been prepared, and for details of their manufactures. These firms include the General Electric Co., Messrs Nalder Bros., Messrs

Evershed & Vignoles, Messrs Johnson & Phillips, and a few others to whom acknowledgment is made in the text.

The author will be glad to receive suggestions and criticisms from teachers and others with respect to those parts of the text which, in their opinion, might be improved. He wishes to acknowledge the assistance he has received from the general editors and is under a special obligation to his friend and former colleague, Dr Chas. F. Smith, for reading through the MSS. and making many valuable suggestions.

FRANK SHAW.

MANCHESTER.

CONTENTS

The paragraphs marked with an asterisk are of a slightly more advanced character than the rest and may be omitted on a first reading.

ELECTRICAL ENGINEERING

CHAPTER I

THE ELECTRIC CURRENT

THE Simple Cell.—The simplest method of producing an electric current is as follows: a copper plate and a zinc plate are placed in a vessel containing some dilute sulphuric acid in such a way that the plates do not touch one another. A metal wire, say of copper, is used to connect the two plates together outside the liquid. When the wire is so connected the following results may be observed: firstly, the wire will become heated to a temperature above the surrounding air, and if the wire be not too long this warming may be detected by the hand; secondly, if the wire be dipped into iron filings, some of these will be found to cling to it; thirdly, while the wire and the copper and zinc plates are connected together, bubbles of gas may be seen to rise through the liquid, starting from where the copper plate touches it. These three effects are said to be the result of an electric current passing through the wire and through the liquid.

The two plates and the acid constitute a simple cell or primary cell. The two plates are sometimes termed electrodes. A number of such cells connected together may be made to produce more powerful effects; such an arrangement is termed a battery or a Voltaic battery, because Volta was the first to adopt it.[1] The results produced by one such cell as has been described are rather feeble, and in many cases it is necessary to combine a number of cells to obtain a reasonably large effect. For convenience, it is usual to regard the electric current obtained from a cell as flowing round the circuit in a definite direction. This direction is from the negative

[1] A single cell is sometimes called a battery; this is a mistake. Nobody would call a single gun a battery.

electrode through the liquid to the positive electrode. From the positive electrode the current flows through the outside circuit back to the negative.

In order to represent a cell in a drawing, the convention universally adopted is shown in Fig. 1. The plate from which the current leaves the cell is known as the positive (+) electrode or plate, and this is represented in the diagram by the long thin stroke. The plate where the current re-enters the cell is called the negative (−) electrode and is denoted by the short thick stroke. In the simple cell, the current flows from the zinc to the copper inside, and from that to the zinc outside. Although it is usual to speak of a cell or a dynamo as a generator of electricity, it would be more correct to say that they generate an *electro-motive force* (abbreviated to E.M.F.) which tends to set electricity in motion and causes it to flow round the circuit.

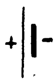


Fig. 1.

Polarisation.—After a simple cell such as that described above has been in use for some time, it will be found that the intensity of the effects produced has decreased, and to explain this result we shall have to examine what happens inside the cell. In the first place, it was remarked that bubbles of gas were seen to rise through the liquid when the circuit was closed. If these bubbles be tested, they will be found to consist of hydrogen gas which must come from the sulphuric acid. Further, the zinc will be found after some time to be eaten away. We conclude from this that the zinc dissolves in the acid and forms zinc sulphate, hydrogen being liberated. Now, although most of this gas passes out through the liquid into the air, some will adhere to the copper plate and cover it with a film of hydrogen. This film is the cause of a *counter E.M.F.* which tends to set up a current in the reverse direction to that caused by the zinc, so that the current given by the cell is decreased. In this condition, the cell is said to be polarised, and where cells are required to send steady currents, arrangements must be made for removing or absorbing this hydrogen as fast as it is produced. The agent which accomplishes this is called a *depolariser*. The copper plate of a simple cell will be found to be unaltered as a result of the working, while on the other hand the zinc must be periodically renewed. The zinc, in fact, acts as a fuel, and is the source of the energy which is produced in the circuit. The acid, too, will after a time require renewing, because when it has all been changed into zinc sulphate, no more zinc can be dissolved, and the current will not flow.

Conductors and Insulators.—Having thus acquired some

dea of one of the methods of producing a current, it will be vorth while to consider more in detail the conditions which ire necessary for the flow of electricity. Referring to the experiment described on page 1, it will be found that the hree effects there alluded to will disappear if the wire be cut. Evidently, then, it is necessary to have a continuous metallic connection from one plate to the other; in other words, the current will not pass through air. Experiment shows that some substances allow a current to flow through them more readily than others. It is customary to speak of a substance, which allows a current to flow through it, as a conductor, and of a substance which does not allow current to flow through it, or one through which current flows with difficulty, as an insulator. Perhaps the best way for the beginner to realise the meaning of these terms is to consider the analogous case of the flow of heat. Common experience tells us that a piece of metal allows heat to pass through it easily, while a piece of wood or glass does not conduct nearly so well. Just as copper or iron conducts heat better than glass or wood, so certain substances are better electrical conductors than others. In fact, the analogy may be extended, because as a rule, substances which are good conductors of heat are good conductors of electricity, and, on the other hand, materials like wood and rubber which do not conduct heat well, are bad conductors of electricity. It must be understood that there is no sharp dividing line between conductors and insulators: it is all a question of degree. Further, some substances which are insulators at ordinary temperatures become partial conductors when strongly heated; glass is a familiar example.

The following is a list of common substances placed in the order of their conducting powers, the best conductor being at the top of the list:—

Copper.
Other metals.
Alloys.
Carbon.
Water.
The body.
Cotton.
Wood.
Paper.
Porcelain.
Ebonite.
Glass.
Air.

The conducting power of a substance depends a good deal upon its dryness. For instance, cotton, wood, leather, etc., lose their insulating properties to a large extent when moistened.

The Electric Circuit.—As suggested on page 3, before any current may be obtained from a cell, it is necessary to have a complete circuit. A circuit in which there is only one path for the current to flow, such as that obtained when the terminals of a simple cell are connected by a wire, is termed a simple circuit. It may be proved by experiment that in such a circuit the intensity of the heat produced and the strength of the action on iron filings are the same at all points along the length of the copper wire. Hence, in this case the strength of the current is the same at all points of the circuit.

The strength of an electric current is measured in terms of a unit named the *ampere*.

Electro-motive Force; Potential Difference.—Whenever an electric current is flowing in a circuit, there must be, somewhere in the circuit, a source of electro-motive force, such as a cell or dynamo. Suppose a simple cell is sending current through a wire, and two points on the wire some distance apart be indicated by *a* and *b*. When the current is flowing in the direction from *a* to *b*, the point *a* is said to be at a higher potential than the point *b*, and there is a difference of potential between the two points. Here again the heat analogy will be helpful. If the temperature at one part of a body is higher than that at another, heat will flow from the hot to the cold place, and the flow will tend to equalise the temperatures. Just in the same way the electricity is regarded as flowing from a point where the electrical potential is high, to a point of lower potential, but if there be an E.M.F. in the circuit, the potentials at the two points never become equalised, and the current continues to flow. Potential difference or E.M.F. is generally measured in terms of a unit named the *volt.*

Resistance.—In order that an electric current shall be set up in a circuit, we have seen that two conditions are necessary—(1) there must be a source of E.M.F.; and (2) the circuit must be closed. Now the strength or intensity of the current will depend upon the magnitude of the E.M.F. and upon the character of the circuit. If a circuit containing a constant E.M.F. be altered in any way, either in regard to the materials of which it is composed, or in regard to the length or cross sectional area, or in regard to the temperature, so that the current is increased, the resistance of the circuit is thereby reduced.

The resistance of circuits is measured in terms of a unit named the *ohm.*

Ohm's Law.—The relation between the E.M.F. and the current in metallic circuits was investigated by Dr. Ohm. He found that so long as the temperature remains unaltered, the current is proportional to the E.M.F. acting in the circuit, or, in other words, that the ratio $\frac{\text{E.M.F.}}{\text{current}}$ is constant. This ratio is called the resistance of the circuit.

In symbols—

$$R = \frac{E}{C} \quad (1)$$

where E is E.M.F., C is current, and R is resistance.

From (1) we have by ordinary algebra—

$$C = \frac{E}{R} \ (2) \quad \text{and} \quad E = CR \ (3).$$

The units of E.M.F. current and resistance have been so chosen that if the E.M.F. is in volts, and the resistance in ohms, the current will be given in amperes.

The student of electrical engineering must make himself thoroughly familiar with the law explained above before he proceeds further. He should work out a large number of examples and be able to apply the equations mentally. The examples below will help to make the law clear.

Example 1.—A dynamo generating an E.M.F. of 230 volts is placed in a circuit, the resistance of which is 5.8 ohms; calculate the current flowing.

$$C = \frac{E}{R} = \frac{230 \text{ volts}}{5.8 \text{ ohms}} = 39.7 \text{ amperes.}$$

Example 2.—What E.M.F. must a cell give in order that it may send a current of 0.03 ampere through a bell circuit of resistance 49 ohms?

$$E = C \times R = 0.03 \times 49 = 1.47 \text{ volts.}$$

Example 3.—In a high voltage continuous current transmission system the E.M.F. necessary to send the current through the line is 2800 volts. If the current is 200 amperes, what is the resistance of the line?

$$R = \frac{2800 \text{ volts}}{200 \text{ amperes}} = 14 \text{ ohms.}$$

Difference between E.M.F. and P.D. — Consider the case

of a cell of constant E.M.F., E connected to a circuit, the resistance of which is R. Let r be the internal resistance of the cell.

$$\text{Total resistance of circuit} = r + R.$$

$$\text{Current } C = \frac{E}{r+R} \quad (4)$$

Now, since the outside circuit is connected across the terminals of the cell, the fall of potential through the outside circuit, or the difference of the potential between the terminals of the cell V, is given by—

$$V = R \times C \text{ by Ohm's law.}$$

Therefore $$V = R \times \frac{E}{r+R} \text{ (from 4 above).}$$

Thus the difference of potential across the terminals of the cell is not necessarily equal to its E.M.F.

Further, $E = C\,(r + R)$
whilst $V = C.R$;
therefore $E - V = C\,(r + R) - CR = C.r.$

This quantity $E - V$ is called the *internal drop*, and is the E.M.F. required to send the current through the cell itself. There are two cases in which E is equal to V, viz., when either C or r is zero. In the former case the cell is open circuited; in the latter the internal resistance is zero.

The principle explained here applies to dynamos in exactly the same way as to cells. Although the internal resistance of a cell or dynamo is never zero, its value may be so small that E and V differ by a negligible amount.

EXAMPLES

(1) Give examples illustrating the distinctions between the E.M.F. of a current-generator, and the P.D. between its terminals. (C & G) (E).

(2) A current of 500 amperes is passing through a cable of 1 square inch cross-section and 100 yards long. Calculate the "drop" produced if the resistance is .045 ohm per mile. What is the current density?

(3) Define shortly, E.M.F., resistance, and current. (C & G) (E).

(4) State the several phenomena which indicate that a current of electricity is passing through a conducting wire or cable. On what grounds are we justified in saying that a current flows in one direction or the other? (C & G) (E).

(5) State Ohm's law and say whether it applies accurately to varying or alternating currents as well as to steady currents. If not, why not? (C & G) (E).

CHAPTER II

MAGNETISM

Properties of Magnets.—Most people are familiar with th fact that a magnet will attract pieces of iron and steel, an lift them if they are not too heavy. A magnetised strip o steel, which is pivoted at its centre and able to turn round vertical axis, is termed a compass needle, and such a need may be used to investigate the properties of magnets. magnet made of a straight bar of steel is conveniently name a bar magnet, and one of these suspended by a fibre attache to its centre will act as a compass needle, and will set itse approximately in a north or south direction. In the exper ment described below, either a suspended magnet or a compa needle may be used.

Attraction and Repulsion.—It will readily be noticed th when a suspended magnet is disturbed, it will sooner or lat come back to the position in which its length is approximatel north and south, and, further, it will be found that the sam end of the magnet will always point north. This end may b marked N, and for convenience is termed the North Pole. Th opposite end is, of course, called the South Pole. Both magne having been tested in this way, it will be found that when th north pole of the bar magnet is presented to the north pole o the suspended magnet, repulsion will ensue. Similarly, th south poles will repel one another. When poles of opposi characters are placed near each other, it will be seen that the is an attraction between them. These results may be summarise by saying that "like poles repel and unlike poles attract."

North and South Poles.—The action of a suspended magn in pointing north and south may be regarded as an examp of attraction and repulsion. The earth acts as if there were large bar magnet inside it, which is nearly coincident with th axis of rotation of the earth. From the explanation give above, it will be understood that the magnetic pole at th north is the same kind as that which we call the south po

of a magnet. For this reason the north pole of a magnet is sometimes termed the north-seeking pole. If a bar magnet be plunged into iron filings, or among small pieces of iron, a number of these will be found to cling to it, especially near the ends, while there will be no evidence of magnetism in the middle. The poles are really regions on the magnet where the filings adhere. While for many purposes it is sufficiently accurate to regard the poles as being at the ends, it must be remembered that this is an assumption made for the sake of simplicity.

Unit Magnetic Pole.—Imagine that two bar magnets, the length of each being great in comparison with the thickness, are placed in air with their north poles presented to each other, and separated by a distance of 1 centimetre. If the strength of the poles is the same, and they repel each other with a force of 1 dyne, they are said to have unit strength.

Permanent and Temporary Magnets.—While it is true that both iron and steel may be magnetised, there is considerable difference between the behaviour of a piece of soft iron and a piece of hard steel after magnetisation. It is possible to magnetise soft iron much more easily than hard steel, but the former loses a large portion of its magnetic power directly the magnetising influence is removed, while in the case of hard steel a large proportion is retained. For this reason a magnet of iron or soft steel is sometimes termed a temporary magnet, and is said to be magnetised by *induction.* On the other hand, a hard steel magnet is said to be *permanent*, because it is difficult to make it lose its magnetism. This matter is referred to later in connection with the manufacture of permanent magnets.

Induced magnetism, as the temporary magnetism of soft iron is called, may be illustrated by a simple experiment. If some small nails made of soft iron be taken, and one of them placed against one of the poles of a bar magnet, it will adhere. A second nail placed against the first will hang down from it, and in this way a chain of perhaps half a dozen may be built up. If the chain be held by the top member, and the bar magnet removed, the nails will all fall down. The top nail is temporarily magnetised by the steel magnet, the south pole of one coming against the north pole of the other. The second nail is magnetised by the first and so on. When the bar magnet is withdrawn, only a small fraction of the magnetism is retained, the amount depending upon the hardness of the nails, and, as a consequence, the force is insufficient to support the weight of the chain.

Examples constantly occur in electrical engineering in which

pieces of soft iron are temporarily magnetised; for instance, the armature core of a dynamo and the iron bars which form the plungers in the solenoids of arc lamps.

Magnetic Field—Lines of Force.—In order to introduce the conception of a magnetic field the student should carry out the experiment described below. A bar magnet is placed below a sheet of white card on which a number of iron filings are scattered; then the card is tapped. The filings will be found to set themselves in a pattern such as that illustrated in Fig. 2. When the filings are in the neighbourhood of the bar magnet, they are magnetised by induction. When they are freed by the tapping of the card, they set themselves with their south poles pointing towards, and their north poles pointing away from, the north pole of the bar magnet. The space surrounding a magnet is termed a magnetic field, and the direction in which the filings set themselves at any point is the direction which a compass needle would take up, and is called the direction of the field. If a compass needle placed near a bar magnet be moved from the position it would naturally take up, it tends to return to its normal position. It will be readily understood that the nearer the compass is to the magnet, the more strongly will it resist being displaced from its position of rest and the quicker it will vibrate about that position. The force which acts on each pole of the compass needle depends on the strength of the magnetic field. This strength is measured by the force in dynes which the field exerts on a unit magnetic pole and is denoted by the symbol H.

A method of explaining the interaction of magnets which is of great use in electrical engineering will now be described. It is supposed that the space near a magnet—the magnetic field—is filled with lines or tubes of force, the direction of these lines being at any point the direction of the magnetic field. Further, the strength of the field is measured by the number of these lines which cross a unit of area perpendicular to the direction of the magnetic force. The number of lines of force at any place crossing each centimetre of area is taken as being numerically equal to the force in dynes on a unit magnetic pole placed at the point in question. The student must be warned against attributing any material existence to these lines of force which are a mathematical invention and serve to show the direction in which a magnetic pole will tend to move. Lines of force are often referred to as *flux*, and the number of lines crossing unit area is spoken of as the flux density. The flux density may either be given in lines per square centimetre or lines per square inch, and is always denoted by the symbol B. When B expresses

Fig. 2

MAGNETIC FIELD DUE TO BAR MAGNET.

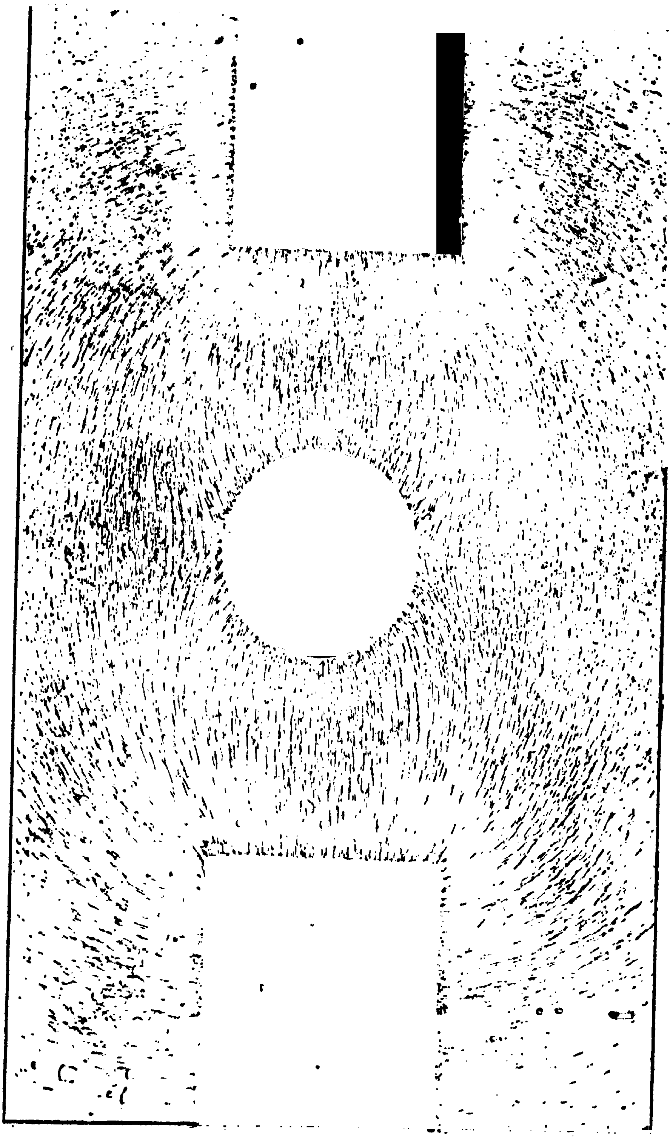


Fig. 3*a*. DISTRIBUTION OF LINES OF FORCE WITH SOFT IRON PLACED IN MAGNETIC FIELD.

the lines per square centimetre in air, it is numerically equal to H.

At a later stage the student will learn how to measure the flux density and how to calculate the flux produced under various conditions.

Shielding.—In Fig. 3*a* is shown the modification produced in the distribution of the lines of force by placing a piece of soft iron in the neighbourhood of a magnet. It will be noticed that the general effect is for the lines to crowd into the soft iron. Experiment shows that the attraction or repulsion between two magnets is not interfered with by placing various substances such as glass, wood, or brass between them. If it is desired to shield any space from the action of magnets in the neighbourhood, this may be done to a large extent by interposing sheets of soft iron; the thicker the iron the more perfect will be the protection.

Fig. 3*b* is intended to illustrate the shielding effect of soft iron. A ring of iron like a large thick washer was placed between the poles of the magnet. The lines are seen to crowd into the iron as in Fig. 3*a*, but inside the ring the filings have not set themselves in any particular direction, thus showing that the field there is very weak.

Certain types of electrical instruments such as amperemeters and voltmeters are often provided with cast iron cases to shield them from the effects of external magnets and electric currents.

Manufacture of Permanent Magnets.—In the older textbooks, methods of making magnets by stroking are described, but in practice the magnetisation is always done electrically. For bar magnets the metal is placed inside a coil of wire and a very large current passed for a short time. The process is known as "flashing," because when the current is stopped there is a bright spark at the point where the circuit is broken. For horse-shoe magnets the poles are placed against those of a powerful electro-magnet, and the current switched on. It is said that there is a slight advantage in repeating the operation two or three times, and also in tapping the steel.

Magnets are subjected to various processes either before or after magnetisation with the object of "maturing" or "ageing" them, or putting them into such a state that the tendency to lose their magnetism is reduced to a minimum. The most usual process is to place them in boiling water or steam for about twelve hours.

Good permanent magnets, if properly treated, will remain constant for years, but they must never be subjected to mechanical shocks or continued vibration. Placing magnets

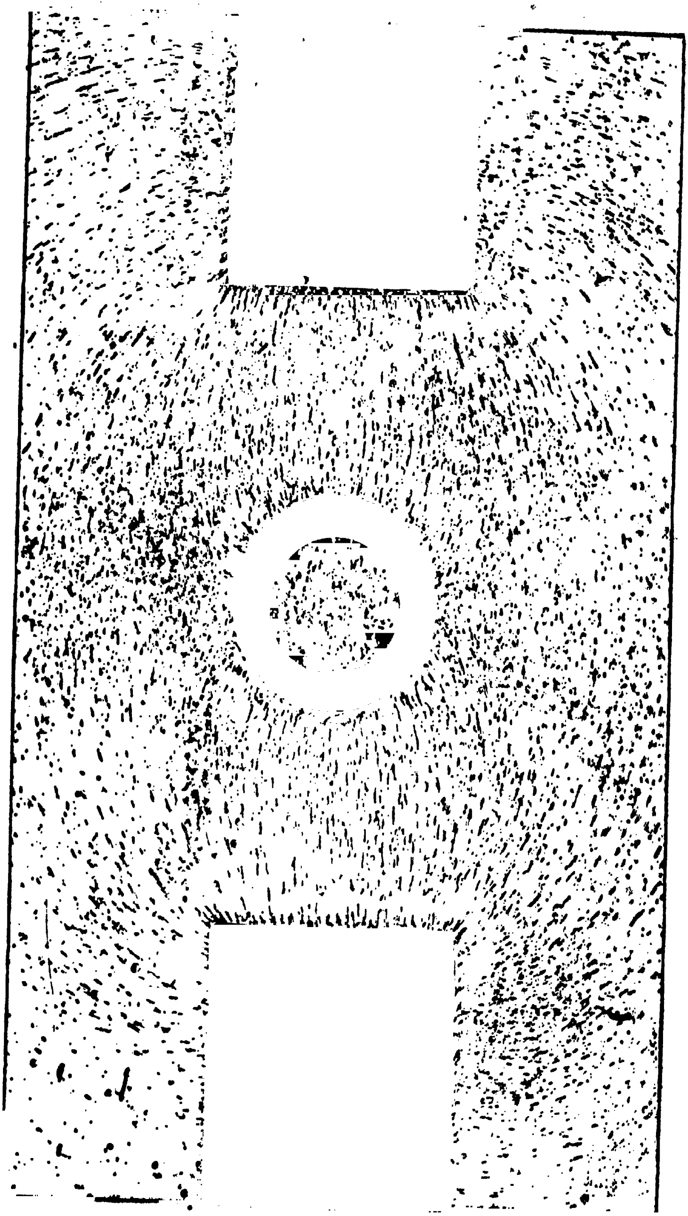


Fig. 3b. To Illustrate Screening Effect of Soft Iron.

or instruments containing magnets near a dynamo or motor should always be avoided, as should also excessive changes in temperature.

The steel used for making permanent magnets is akin to tool steel in that it is capable of being hardened by quenching. The term "steel" has become somewhat indefinite of recent years, because the material used for making the armature cores of dynamos is often called steel or mild steel, although it is a remarkably pure form of iron. The student must carefully distinguish between this soft steel and the steel used for making permanent magnets. This latter may be called "hardenable" steel, and may be either a steel containing a high percentage of carbon, say 0.5 – 1.5, or an alloy consisting of this steel with tungsten or vanadium. In view of the large number of permanent magnets used for electrical instruments and magnetos, many firms now make a special brand which they term "magnet" steel. It has been stated that a tungsten steel containing 5 to 8 per cent. of tungsten, and 0.4 – 0.6 per cent. of carbon is the best for magnets which are to be both powerful and constant. An important question is the shape. Short magnets are found to lose their magnetism much sooner than long ones, and are more easily affected by shocks. In addition to making permanent magnets as long as possible, it is an advantage for the shape to be such that the poles come near together, or, in other words, for the air gap to be as short as possible. The larger the area of this gap the smaller will be the number of lines per square centimetre in the air, and the more permanent will the magnet be. For this reason, bar magnets used for experimental purposes are usually kept in pairs in a box with a soft iron bar or "keeper" at each end. The keepers form with the magnets a complete steel and iron circuit through which nearly all the magnetic lines pass, and the effect of external influences is reduced.

EXAMPLES

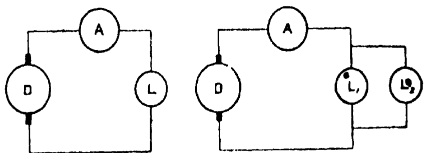
(1) Give the definition of the terms "magnetic lines of force" and "the intensity of magnetic field." Why do the patterns obtained by sprinkling iron filings on cardboard or glass not accurately represent the magnetic lines of force? (C & G) (E).

(2) Give a detailed account of the complete method of constructing a permanent magnet to be used in a moving coil ammeter. (C & G) (O).

CHAPTER III

THE ELECTRIC CIRCUIT

Simple and Complex Circuits.—For the purpose of explaining the production of a current in chapter i., the simplest type of circuit was considered. By a simple circuit is meant one in which the current has only one path in which to flow; in such a circuit the strength of the current will be the same at all points. In a simple circuit the various parts are said to be connected in series. Fig. 4 (*a*) shows a typical simple circuit



(*a*) (*b*) Fig. 4.

containing a dynamo, an ampere-meter, and a lamp. Now suppose that instead of having only one lamp as shown, another lamp is placed with its terminals connected across those of the first lamp (*b*). The current will in this case divide between the two lamps and by symmetry, if these are alike, the current in each will be of the same strength, and, as will be learnt later, will be half the total current. The two lamps are said to be connected in parallel. Before explaining the laws governing series and parallel circuits, one or two practical cases may be examined. In Fig. 5 three generators, *a*, *b*, *c*, are connected in series. All three are tending to send current round the circuit in the same direction, and the current through all three must be the same. Now suppose that the E.M.F.'s developed by these three generators are 250 volts, 240 volts, and 20 volts respectively, and that the total resistance of the circuit is 60 ohms. The total E.M.F. will be 250 + 240 + 20 = 510 volts, and

$$\text{current} = \frac{510 \text{ volts}}{60 \text{ ohms}} = 8.5 \text{ amps.}$$

As another illustration, consider the case of a dynamo connected to a battery for the purpose of charging it. The E.M.F. of the dynamo is 265 volts. There are 110 cells, and the E.M.F. of each cell is 2.2 volts. The resistance of each cell is 0.012 ohm, resistance of dynamo and connections, $\frac{1}{4}$ ohm. Calculate the current.

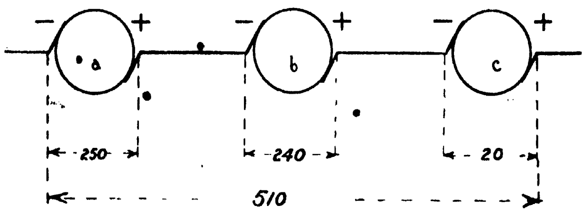


Fig. 5.

The E.M.F. of the cells will oppose that of the dynamo since the former are going to be charged, hence

$$265-(110 \times 2.2)=C \times (110 \times 0.012+0.25)$$

where C is the current.

$$265-242=C\ (1.32+0.25)$$

$$C=\frac{23}{1.57}=14.65 \text{ amps.}$$

Kirchhoff's Laws.—In the foregoing examples, we have assumed two laws which may be formally stated as follows:—

(1) The algebraic sum of the currents meeting at any point in a network of conductors is zero.
(2) The algebraic sum of the E.M.F.'s acting in any circuit is equal to the sum of the products of the currents in, and the resistances of, the separate parts.

The first law means that the total amount of current approaching any point is equal to the total amount of current flowing away from the point, or, in other words, that there can be no accumulation of electricity anywhere.

The example which follows will help to make the second law clear.

A dynamo is connected to a motor by cables, the resistance of which is 2.5 ohms. The resistance of the dynamo armature is 0.2 ohm, and of the motor armature 0.3 ohm. The field windings are connected as shown (Fig. 6), and carry 1 ampere

in each case. The E.M.F. of the generator is 250 volts, and a current of 10 amperes passes from the dynamo to the motor. Calculate the back E.M.F. of the motor.

Current in dynamo armature $= 10 + 1 = 11$ amps.
Current in motor dynamo $= 10 - 1 = 9$ amps.

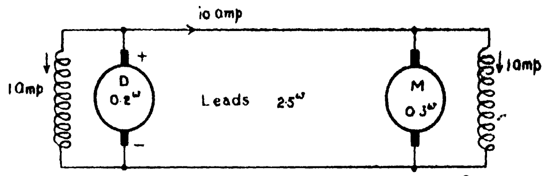


Fig. 6.

TO ILLUSTRATE EXAMPLE ON ELECTRIC CIRCUIT.

Applying the law :—

Algebraic sum of E.M.F.'s = Current in dynamo armature × resistance of armature + current in cables × resistance of cables + current in motor armature × resistance of motor armature.

Calling the required back E.M.F. e,

$$250 - e = 11 \text{ amps.} \times 0.2 \text{ ohm} + 10 \text{ amps.} \times 2.5 \text{ ohm} + 9 \text{ amps.} \times 0.3 \text{ ohm}.$$

$$2.2 + 25 + 2.7 = 30 \text{ volts nearly.}$$

Therefore $e = 250 - 30 = 220$ volts.

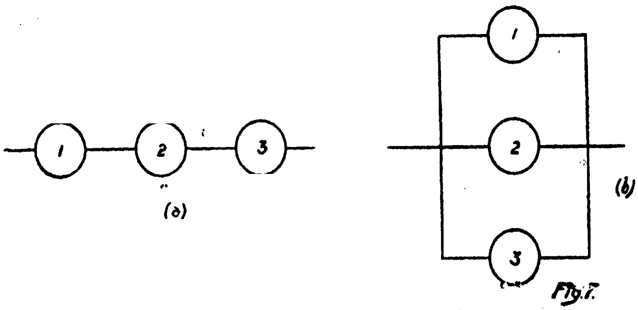


Fig. 7.

This is the back E.M.F. developed by the motor.

Series and Parallel Circuits.—Circuits may be combined in two simple ways. For example, three lamps may be connected as in Fig. 7 (a) or (b). In (a) the lamps are said

to be connected in series, in (b) they are connected in parallel. Notice that in (a) the current through each lamp is the same, while in (b) the P.D. across each lamp is the same. Suppose now that r_1, r_2, and r_3 represent the resistances of the three lamps, and it is required to know the resistances of the three in combination first of all in series. Imagine a current c amperes passing through the group. Then by Ohm's law the drop of potential in (1) $e_1 = c \times r_1$, that in (2) $e_2 = c \times r_2$, and that in (3) $e_3 = c \times r_3$.

By Kirchhoff's law the total drop $E = e_1 + e_2 + e_3$.

But if R is the resistance of the combination $E = C \times R$,

then $$C \times R = c \times r_1 + c \times r_2 + c \times r_3 = c\,(r_1 + r_2 + r_3).$$

therefore $$R = r_1 + r_2 + r_3,$$

or the resistance of the circuits in series is the sum of their individual resistances.

If there are n circuits of the same resistance ($= r$), the total resistance $R = n \times r$.

Example.—Three lamps of resistances 55, 70, and 130 ohms respectively are connected in series. What is the combined resistance?

$$R = 55 + 70 + 130 = 255 \text{ ohms.}$$

Turn now to the case of the parallel grouping. As before, the resistances of the individual circuits r_1, r_2, and r_3. Let the P.D. across each circuit be E. If R be the resistance of the combination and C the total current, $C = \frac{E}{R}$. Let c_1, c_2, and c_3, be the currents through the circuits. By Kirchhoff's first law

$$C = c_1 + c_2 + c_3\,; \text{ also } c_1 = \frac{E}{r_1},\ c_2 = \frac{E}{r_2},\ c_3 = \frac{E}{r_3}.$$

$$\therefore \frac{E}{R} = \frac{E}{r_1} + \frac{E}{r_2} + \frac{E}{r_3} \text{ and } \frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}.$$

Now the reciprocal of the resistance of a circuit is called the *conductance*. In this case the rule is: the joint conductance is the sum of the conductances of the individual circuits.

The combined resistance of n circuits connected in parallel, the resistance of each circuit being r, is given by

$$R = \frac{r}{n}.$$

If there are only two circuits to be considered, we have—

$$\frac{1}{R}=\frac{1}{r_1}+\frac{1}{r_2}=\frac{r_1+r_2}{r_1 r_2}$$

$$\therefore R=\frac{r_1 \times r_2}{r_1+r_2}$$

a result which is often required. Expressed in words: the joint resistance is the product of the individual resistances divided by their sum.

Example.—A galvanometer of resistance 40 ohms is connected in parallel with a shunt of resistance 1.3 ohms. Calculate the joint resistance.

$$R=\frac{1.3 \times 40}{1.3+40}=1.24 \text{ ohms.}$$

Resistance of Conductors — Specific Resistance. — The rules given above for obtaining the resistances of circuits in combination may be applied to discover the relation between the resistance of a conductor and its length and cross-sectional area. Consider a number of conductors of the same cross-sectional area, each having unit length and resistance (r). From the rule given in the last paragraph, the resistance of any number of circuits (n) connected in series will be given by $R=nr$, but since each conductor is one unit long, n = length of conductor, therefore $R \propto n$ or $R \propto l$, that is, the resistance of a conductor of constant cross-section is directly proportional to its length. In a similar way, taking (n) conductors of the same length, each of resistance (r) and cross-sectional area unity, connected in parallel

$$R=\frac{r}{n}$$

Now (n) conductors, each of unit cross-sectional area, are equivalent to one conductor of total cross-sectional area (n), therefore since

$$R \propto \frac{1}{n} \quad R \propto \frac{1}{\text{c.s a.}}$$

that is, for constant length the resistance is inversely proportional to the cross-sectional area. Combining these results, and calling the cross-sectional area a, we have—

$$R \propto \frac{l}{a}$$

This may be written $R = \frac{sl}{a}$, where s is a constant; that is to say, it is independent of l and a. The constant "s" is called the *specific resistance* or the *resistivity* of the substance of which the conductor is made.

If in the above formula $l = 1$ and $a = 1$,

$$R = \frac{s \times 1}{1} \text{ or } R = s;$$

the specific resistance, therefore, is the resistance of a conductor of unit cross-sectional area and of unit length. It has different values for different substances, and for a particular substance its value varies with the temperature.

Below is given a table showing the resistivities of various substances at 0°C. The values given in the second and third columns are the resistivities in inch and centimetre measures respectively. When using the values given in the first column, the length and cross-section of the conductor must be put in inches and square inches respectively; when using those in the second column, centimetres and square centimetres must be used. The values for copper are those adopted by the Engineering Standard Committee, the other figures are taken chiefly from Dewar and Fleming's results.

TABLE OF RESISTIVITIES OF METALS AND ALLOYS AT 0°C.

Metal.	Inch Measure.	Centimetre Measure.	Temperature Coefficient.
Copper (annealed)	0.626×10^{-6}	1.59×10^{-6}	0.00428
Copper (hard drawn)	0.638 ,,	1.623 ,,	,,
Aluminium	1.05 ,,	2.66 ,,	0.00435
Iron	3.57 ,,	9.06 ,,	0.0062
Platinum	4.29 ,,	10.9 ,,	0.00367
Tin	5.12 ,,	13.0 ,,	0.0044
Lead	8.03 ,,	20.4 ,,	0.0041
Mercury	37.1 ,,	94.1 ,,	0.00098
*German Silver. [Cu 60%, Zn 25%, Ni 14%]	8.6 ,,	22.0 ,,	0.00044
Manganin [Cu 84%, Ni 4%, Mn 12%]	16.5 ,,	42.0 ,,	0.00001
Eureka [Cu 58%, Ni. 42%]	18.5 ,,	47.0 ,,	0.000005
Nickel-Chrome	33.4 ,,	85.0 ,,	0.00024

* The data concerning these alloys are based on information kindly supplied by the makers—The London Electric Wire Co. and Smiths, Ltd.

Example.—What is the resistance of a mile of trolley wire (hard drawn copper) $\frac{1}{3}$ inch in diameter?

$$R = \frac{0.638}{10^6} \times \frac{5280 \times 12}{(\frac{1}{3})^2 \times .0785} = 0.464 \text{ ohms.}$$

Example.—A coil of eureka wire No. 26 gauge (sectional area 0.000254 square inch) is required to have a resistance of 10 ohms. What length will be required?

$$10 = \frac{18.5 \times l}{10^6 \times 0.000254 \text{ sq. in.}}$$

$$l = \frac{10^7 \times 0.000254}{18.5} = 137 \text{ ins.}$$

Example.—The resistance of the filament of a tantalum lamp is 53 ohms when cold, and it is 0.05 millimetre diameter. The length is 65 centimetres. Calculate the resistivity of tantalum.

$$s = \frac{R \times a}{l} = \frac{53 \times .785 \times (.005)^2}{65} = 16 \times 10^{-6} \text{ ohms per cm. cube.}$$

Resistance and Temperature.—Reference has been made to the fact that the resistivity of a substance is not a constant, but depends upon its temperature. In the case of all pure metals the resistance increases as the temperature increases, and over a considerable range the increase in resistance is proportional to the increase in temperature.

If R_0 be the resistance of a conductor at 0° C, and R_t its resistance at $t°$ C, the relation between R_0 and R_t is given by

$$R_0 = R_t (1 + at)$$

In this expression a is called the temperature coefficient. When the resistance increases with temperature a is positive; when the resistance decreases with temperature it is negative. The values of a for various substances are given in the table on p. 21. Using this table the resistance at one temperature may be calculated if the resistance at 0° C or any other temperature is known.

Example.—The resistance of the field winding of a dynamo is 58 ohms at 35° C. What is its resistance at 0° C and at 15° C? The value of a for copper is 0.00428.

$$R_t = R_0 (1 + at), \quad 58 = R_0 (1 + 0.00428 \times 35)$$

$$R_0 = \frac{58}{1 + 0.15} = \frac{58}{1.15} = 5.04 \text{ ohms.}$$

Using this value for the resistance at 0° C we may calculate the resistance at 15° C.

$$R_{15} = R_0\ (1 + 0.00428 \times 15)$$
$$= 50.4 \times 1.064 = 53.7 \text{ ohms.}$$

Example.—The resistance of a coil of a platinum thermometer is 5 ohms at 15°C. At a certain temperature it is measured and found to be 6.38 ohms. What is that temperature?

Let a be the temperature coefficient, then

$$5 = R_0\ (1 + 15\ a) \quad (1)$$
$$6.38 = R_0\ (1 + t\ a) \quad (2)$$

These are two equations from which R may be eliminated and t determined.

Dividing (2) by (1) $\quad \dfrac{6.38}{5} = \dfrac{1 + a\ t}{1 + 15\ a}$

for platinum, $\quad a = 0.0036$

$$\therefore \frac{6.38}{5} = \frac{1 + 0.0036\ t}{1 + 15 \times 0.0036}$$

$$\frac{1 + 0.0036\ t}{1.054} = 1.276$$

$$0.0036\ t = (1.27 \times 1.054) - 1$$

$$t = \frac{(1.27 \times 1.054)}{0.0036} - 1$$

$$= 96° \text{ C.}$$

* The rise of temperature produced in the windings of an electrical machine is often determined by measuring the increase of resistance. The resistance of the winding in question is measured with the machine cold, and again when it has been heated up. The formula developed below will enable the rise in temperature to be obtained directly.

As before let R_0 = resistance of winding at 0° C
R_1 = " " at t_1° C
R_2 = " " at t_2° C

Then $\quad R_1 = R_0\ (1 + a\ t_1) \quad (1)$

and $\quad R_2 = R_0\ (1 + a\ t_2) \quad (2)$

Dividing (1) by (2) $\quad \dfrac{R_1}{R_2} = \dfrac{1 + at_1}{1 + at_2}$

Dividing the numerator and denominator of the right hand side by a

$$\frac{R_1}{R_2} = \frac{t_1 + \frac{1}{a}}{t_2 + \frac{1}{a}}$$

$$\frac{R_1}{R_2} - 1 = \frac{t_1 + \frac{1}{a}}{t_2 + \frac{1}{a}} - 1$$

$$= \frac{t_1 + \frac{1}{a} - \left(t_2 + \frac{1}{a}\right)}{t_2 + \frac{1}{a}}$$

$$= \frac{t_1 - t_2}{t_2 + \frac{1}{a}}$$

$$\therefore \frac{R_1 - R_2}{R_2} = \frac{t_1 - t_2}{t_2 + \frac{1}{a}}$$

Multiplying by $\left(t_2 + \frac{1}{a}\right)$

$$t_1 - t_2 = \frac{R_1 - R_2}{R_2} \times \left(t_2 + \frac{1}{a}\right)$$

Now $t_1 - t_2$ = rise in temperature

and $R_1 - R_2$ = increase in resistance.

$$\therefore \text{rise in temperature} = \frac{\text{Increase in resistance}}{\text{original resistance}} \times \left(\frac{1}{a} + \text{original temperature}\right)$$

For copper $a = 0.00428$

$$\therefore \frac{1}{a} = \frac{1}{0.00428} = 233.$$

Quantity of Electricity.—The rate of flow of water through a pipe may be expressed by stating the quantity which passes any point in a given time, say 10 gallons per minute. The unit of electricity corresponding to the gallon is the *coulomb*, and

$$\text{current (in amperes), } C = \frac{\text{Quantity (in coulombs), Q}}{\text{Time in seconds, } t}$$

$$\therefore Q = Ct.$$

If t is in hours, Q will be given in ampere hours

Power and Work.—When a current of (*C*) amperes flows through a circuit the E.M.F., in which is E volts, the power P or rate of doing work in the circuit is

$$E \times C \quad (1)$$

but since

$$E = CR$$
$$P = C.R \times C$$
$$P = C^2 R \quad (2)$$

or

$$P = E \times \frac{E}{R}$$
$$= \frac{E^2}{R} \quad (3)$$

(1) (2) or (3) are all correct expressions for the power in a continuous current circuit, but sometimes one form is more convenient than either of the others.

If E is expressed in volts and C in amperes the unit of power, 1 volt × 1 ampere, or 1 volt-ampere is termed the watt.

A unit of power frequently used in engineering is the horse power, which is equal to 746 watts. 1000 watts are called a Kilowatt. If the current and voltage are varying, P is the instantaneous value of the power.

Example.—A dynamo supplies 320 amperes at a P.D. of 500 volts. Calculate the rate of working in the external circuit in watts and in H.P.

$$P = E \times C$$
$$= 500 \times 320$$
$$= 16000 \text{ watts}$$
$$H.P. = \frac{16000}{746} = 20.1$$

Example.—Assuming the resistance of a lamp to remain constant, calculate how the power supplied to it is altered by a 10 per cent. increase in voltage.

Let P_1 be the power supplied to the lamp at normal voltage, and P_2 be the power supplied to the lamp at a voltage 10 per cent. above normal; also let V_1 be the normal voltage and V_2 the increased voltage, then—

$$V_2 = \frac{110}{100} V_1$$

Now $$\frac{P_2}{P_1} = \frac{\frac{V_2^2}{R}}{\frac{V_1^2}{R}} = \left(\frac{V_2}{V_1}\right)^2 = \left(\frac{\frac{110}{100}V_1}{V_1}\right)^2 = \frac{121}{100} = 1.21$$

$\therefore$ $P_2 = 1.21\ P_1$, *i.e.*, the power is increased 21 per cent.

Work is measured by the product of power and time. If power be expressed in watts, and time in seconds, then work will be given in *joules*, *i.e.*,

work (joules) = power (watts) × time (seconds).

If the time be expressed in hours and the rate of working in kilowatts, the work is given in KILOWATT-HOURS. The kilowatt-hour has been adopted for the practical measurement of electrical energy, and is known in this country as the BOARD OF TRADE UNIT, written B.O.T. unit. This term is somewhat clumsy, and in practice a K.W. hour is often termed a "unit," which must be regarded as a convenient and rather ambiguous abbreviation for the real expression given above. A short and international term is required, and Hobart has suggested that a K.W. hour should be called a Kelvin.

The relations between these units will be understood from the examples worked below.

Example.—A voltmeter indicating 500 volts has a resistance of 10,000 ohms. Determine the energy wasted in it in a quarter of a year (13 weeks):—

$$\text{Power} = 500^2 \div 10000 = \frac{500 \times 500}{10000} = 25 \text{ watts.}$$

$$\begin{aligned}\text{Energy wasted} &= 25 \times 13 \times 7 \times 24 \text{ watt hours.}\\ &= 54600 \text{ watt hours}\\ &= 54.6 \text{ K.W. hours.}\end{aligned}$$

Example.—If 382 ampere hours at 0.25 volt are required to deposit 1 lb. of copper; calculate the cost of refining copper per ton with electrical energy at 1d. per K.W. hour.

No. of lbs. in 1 ton = 2240.

To deposit 1 lb. of copper requires 382 × 0.25 = 95.5 watt hours; therefore to deposit 1 ton will require

$$\frac{95.5 \times 2240}{1000} = 214 \text{ K.W. hours.}$$

The cost of this will be 214d. = 17s. 10d.

* *Note on C.G.S. Units.*—The student will be already familiar with the C.G.S. units of length, mass, time, force, power, and work.[1]

The electrical units of E.M.F., current, resistance, and quantity introduced in this chapter are derived from the C.G.S. system.

Unit of Current.—Imagine a current flowing through a turn of wire of unit radius 1 centimetre. A magnet pole placed at the centre of the turn will experience a force tending to move it

[1] Information concerning these units will be found in books on mechanics.

in a direction at right angles to the plane of the circle. When the force on a unit magnetic pole is 2π dynes the current is said to have unit value.

The practical unit—the ampere is $\frac{1}{10}$ of this C.G.S. unit of current.

Unit of P.D. or E.M.F.—The unit of E.M.F. is derived from the unit of current and the unit of work. Imagine a current of unit strength flowing through a circuit, and let there be two points, *a* and *b*, between which 1 erg of work is done every second. Then the difference of potential between *a* and *b* is said to have unit value.

The practical unit—the volt $= 10^8 \times$ the C.G.S. unit of E.M.F.

Unit of Resistance.—When unit P.D. between two points produces unit current, the resistance between the points has unit value.

Referring to the last paragraph the resistance of the portion of the circuit between *a* and *b* will be unity.

The practical unit—the ohm $= 10^9 \times$ the C.G.S. unit of resistance.

EXAMPLES

(1) A dynamo maintaining a constant pressure of 220 volts between its terminals, supplies a power of 18,000 watts to a house 200 yards away. What must be the cross-section of the copper of the leads so that not more than 4 per cent. of the power may be wasted in them? The resistance of a cubic inch of copper may be taken as 0.66 microhm. (C & G) (E).

(2) A 90-volt 8-candle-power glow lamp in series with a resistance, is placed across 100-volt constant-pressure mains. On applying a voltmeter between the lamp terminals to ascertain whether the pressure is correct the light diminishes. Explain exactly how this occurs. (C & G) (E).

(3) A cell of E.M.F. 1.5 volts and internal resistance 5 ohms is connected to a circuit which consists of two branches of resistances 100 and 10 ohms respectively. Calculate the current in the cell and in each branch of the circuit.

(4) The resistance of a potentiometer wire has become too high, due to wear, and this may be corrected by shunting it. Calculate the resistance of the shunt if the wire should be 2 ohms but is 1 per cent. higher. What length of manganin wire, at 40 ohms per metre, will be required?

(5) A dynamo supplies current to a set of 100 lamps which are grouped in parallel at a distance of half a mile from the dynamo. The going

and return conductors have each a cross-section of 0.04 square inch, and the resistance of copper may be taken as 0.66 microhm per cubic inch. If a current of 0.2 ampere has to be sent through each lamp, and a P.D. of 220 volts maintained between the terminals of the group, what must be the P.D. between the dynamo terminals? (C & G) (E).

(6) What is the approximate resistance of one mile of No. 16 S.W.G. (0.064 inch diameter) high conductivity copper wire? What current will flow if its ends are connected with a pair of terminals having a difference of potential of 50 volts? The resistance of an inch cube of copper is two-thirds microhm. (C & G) (E).

(7) Write down the terms Work, Force, Power, and Quantity as headings, and then arrange the names of the following units, each under its proper heading. Watt, Kilowatt, Ampere-hour, Horse-power, Kilowatt-hour, Dyne. (C & G) (E).

(8) An overhead transmission line consists of two wires, each 2 kilometres long and 150 square millimetres cross-sectional area. If the continuous current flowing in one, and returning in the other is 150 amperes, what will be the power in watts wasted in the line? The specific resistance of copper is 1.72 microhms per centimetre cube. (C & G) (E).

CHAPTER IV

ELECTRO-MAGNETISM

MAGNETIC Effect of Current through Straight Conductor.— The first discovery connecting electricity and magnetism was made by Oersted, who found that a current flowing through a conductor affects a freely suspended magnet. If the experiment be made of holding a pivoted magnet such as a compass needle near a conductor carrying a current, it is found that the magnet tends to set itself in a direction at right angles to the direction of the current. To take a particular case, suppose the conductor is placed approximately north and south. When the needle is brought sufficiently near the conductor to be affected, it will tend to point east and west if placed above or below the current. If placed at either side of the conductor, the needle tends to set itself vertically.

A simple and useful experiment to illustrate this principle may be carried out as follows: A stout copper wire through which a current of at least 10 amperes may be passed, is held in a vertical position and a piece of white card supported in a horizontal plane, the conductor passing through a hole in the card. If a compass needle be placed on the card at various points near the conductor, it will be found to set itself as shown in Fig. 8.

To illustrate further this important effect, some iron filings may be sprinkled on the card near the conductor. Then the current should be made to flow and the card tapped gently. The filings will be found to set themselves roughly in closed chains as a series of concentric circles, the centre of which is on the axis of the wire, Fig. 9. If a circle is drawn with the centre at the axis of the wire, the compass placed anywhere on this circle takes up a position tangential to it. The iron filings, behave in the same way as the compass needle, being magnetised by the current. Now, the direction in which a compass needle points is the direction of the magnetic force in the vicinity, and a continuous line, the direction of which

is everywhere that of the magnetic force, is termed a line of force.

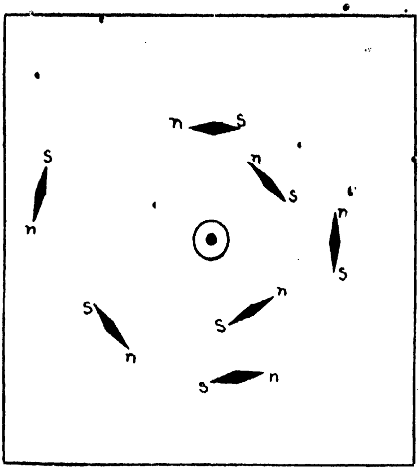


Fig. 8.

POSITION OF COMPASS NEEDLE PLACED NEAR VERTICAL CONDUCTOR CARRYING CURRENT.

The experiments mentioned above show that the lines of force produced by a straight conductor carrying a current are

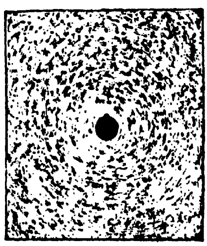


Fig. 9.

MAGNETIC FIELD PRODUCED BY STRAIGHT CONDUCTOR.

a series of concentric circles with a common centre on the axis of the conductor. For diagrammatic purposes it is understood that an arrow placed on a line of force indicates the

direction in which the mechanical force would act upon a north pole.

It will be convenient at this stage to learn a rule for showing the relation between the direction of flow of a current and that of the lines of force produced by it. The simplest is the right-hand-grasp rule, and is as follows: Grasp the conductor with the right hand, letting the thumb point in the direction of the flow of the current, then the fingers will curve round the wire and indicate the direction of the lines of force. This rule may also be used for determining the direction of the current if the way in which a compass needle points when placed near the wire is known.

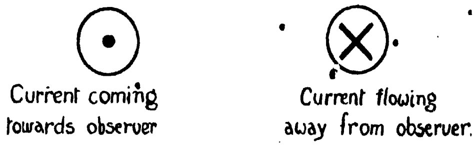
Magnetic Effect of Solenoids.—Having learned something of the effect produced by a current flowing through a straight conductor, take the case in which the conductor is coiled. The rules which have been given still apply, because so long as attention is confined to points very near the wire and only a short length of it is considered, a curved wire will produce the same effect as a straight one. By means of a drawing, only forces which are in one plane can be illustrated, but a convention will enable the direction of forces which are perpendicular to the plane of the paper to be shown. Just as the directions of forces may be indicated by arrows when they are in one plane, so a force acting towards the observer may be indicated by means of a dot, and a force acting away from the observer by means of a cross. The dot represents the point of the arrow, and the cross the feather, *see* Fig. 10.

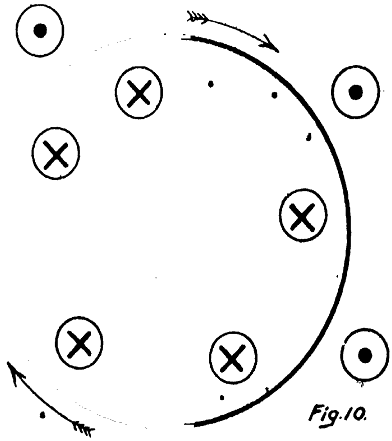
In the same figure is shown a curved conductor carrying a current in the direction of the arrows. Applying the right hand rule to the wire at different places, it will be seen that as shown in the figure, the lines of force have a direction away from us inside the coil, and towards us outside it. In other words, all parts of the coil act together to produce a magnetic field in the same direction inside it. A little consideration will show that if there are two turns of wire instead of one, the effect will be the same as if there were only one turn carrying twice the current. The magnetising force, in fact, depends upon the *ampere turns*, by which is meant the product of the number of turns and the strength of the current flowing through them.

Fig. 10*a* shows the distribution of the lines of force in a plane at right angles to the plane of a coil consisting of a single turn. It will be seen that near the conductor the distribution is similar to that produced by a current flowing through a straight conductor (Fig. 9). Near the centre of the circle the field is uniform, and the lines of force become nearly parallel.

Fig. 10*b* is the case of a helix or solenoid consisting of seven turns. As all the turns produce a magnetising effect in the same direction, the result is a very powerful field inside the coil.

Effect of Iron Cores.—So far we have been considering the magnetic effects produced by currents flowing in conductors supposed to be surrounded by air. Very important





To illustrate Magnetic Field produced by a Single Turn.

modifications are produced by placing masses of iron or steel near such conductors. If an attempt be made to place a rod of soft iron inside a solenoid which is carrying a current, the moment the rod begins to enter the coil it is pulled violently to a symmetrical position inside. On testing the rod while still inside the coil, by means of a compass needle, it would be found to behave like a bar magnet—*i.e.*, it would have a north pole

near one end and a south pole near the other. If the solenoid is tested when it has no iron inside it, it behaves like a much weaker bar magnet. It is not correct to say that the solenoid

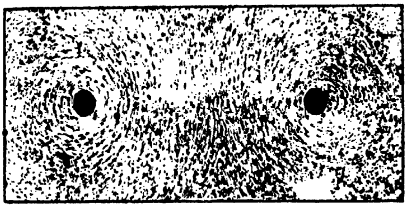


Fig. 10a

MAGNETIC FIELD DUE TO SINGLE TURN.

has a pole at each end, but it acts in many ways as if it had. Thus in addition to producing a magnetic effect itself, the solenoid is capable of *inducing* a piece of soft iron to produce a similar effect. For this reason the iron rod is said to be *magnetised by induction.* The solenoid and the bar of iron inside it form an electro-magnet of a simple kind.

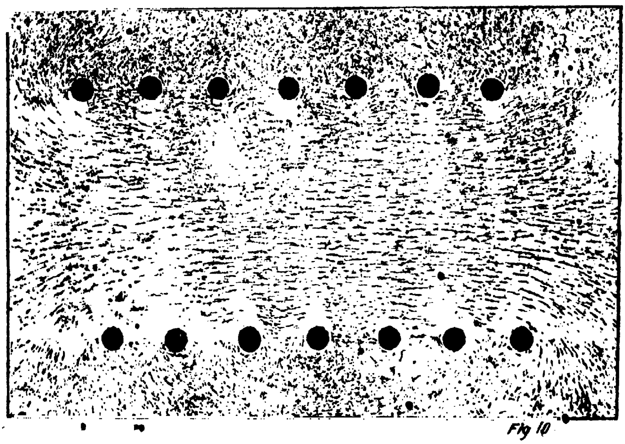


Fig 10

MAGNETIC FIELD INSIDE SOLENOID.

Owing to the fact that the amount of magnetism produced when the rod is present may be many times greater than that produced by the coil alone, iron is always employed in the construction of electro-magnets.

Magnetic Properties of Iron and Steel—Permeability.—It was explained in chapter ii. that the strength of the magnetic field at any point is measured by stating the force acting on a unit pole in dynes, H ; also that the number of lines of force crossing each square centimetre in a magnetic field is indicated by the symbol B. In the case of air, or indeed almost any material except iron or steel or their compounds, B and H are numerically equal. Now consider the effect explained in the previous paragraph. The insertion of the iron bar is found to result in a large increase in the flux produced inside the solenoid. The magnetising force inside remains nearly the same since this depends on the ampere-turns. The conclusion, therefore, is that the ratio $\frac{B}{H}$ for iron is much greater than for air. The ratio $\frac{B}{H}$ is known as the permeability of the material, and is always indicated by the symbol μ. For air $\mu = 1$.

In Fig. 11 is given a graph showing the relation between B and H for two important materials, cast iron and wrought iron or soft steel, such as is used for making armature cores. It will be seen that B increases with H rapidly at first, and then more slowly, the curves exhibiting a well marked bend. At large values of H the iron is said to become saturated, and the permeability is very low. It is left as an exercise for the student to plot graphs connecting μ and B or μ and H.

Hysteresis.—It was explained in chapter ii. that when a piece of soft iron is magnetised, by being placed near a bar magnet, a certain amount of its magnetism will be retained when the bar magnet has been removed. Consider an iron bar to be placed inside a solenoid through which a current is passed. Suppose the current to be gradually increased to a maximum value; the flux produced in the iron will increase as the current increases, though not, of course, proportionally. If now the current be reduced, the flux in the iron will also decrease, but when the current has been brought to zero there will still be some lines of force in the iron. It will be necessary, in fact, to send a small current in the reverse direction to wipe out this magnetism and completely demagnetise the bar. Thus the changes in magnetism, whilst corresponding to the changes in current, lag behind the magnetising force. To this phenomenon the term *hysteresis* has been applied. Hysteresis means a lagging behind, and the term is intended to express the fact that in the case of iron the effect lags behind the cause. It is important for the student to notice that hysteresis does not mean a lagging behind in point of time, since the effects described above will be observed however slowly the changes

take place. When a bar is magnetised, energy is supplied to it, but this energy is not all returned if some of the magnetism is retained when the magnetising force is removed. Thus an absorption of power will accompany hysteresis, and results in

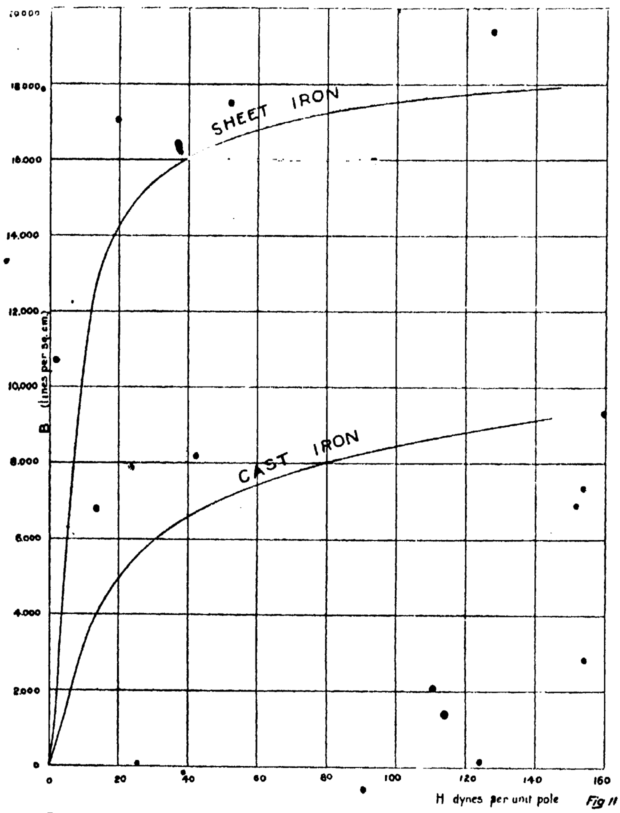


Fig 11

CURVES SHOWING RELATION BETWEEN B AND H FOR SHEET IRON AND CAST IRON.

a bar whose magnetism is being continually changed becoming heated. This will be referred to later in chapter x.

One or two applications of the principle of the electro-magnet will now be described, but it must be understood that electro-magnets enter into the construction in one way or another of most electrical appliances.

Electric Bells.—An electric bell known as a trembling bell is shown in Fig. 12.

The bell illustrated here is manufactured by the General Electric Co. for use in mines, and is provided with a close-fitting cast-iron cover to keep out moisture.

As will be understood from the diagram, the two coils form with the iron frame a small electro-magnet. The iron plate attached to the hammer, known as the armature, is held by the flexible spring and is pulled up to the poles whenever the

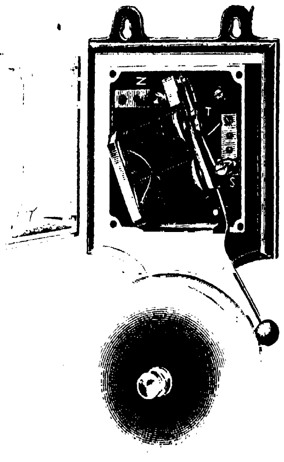


Fig. 12. View of Trembling Bell.

current passes round the coils and magnetises the cores. When the current is stopped, the spring pulls the armature back. The current through the coils passes, in this form of bell, through a contact, which is broken when the armature is pulled up to the poles. Thus a continuous vibration is produced as long as the circuit is closed. When used for ordinary work the current is obtained from one or two Leclanché cells. Another class of bell is one in which there is no automatic contact maker and the current simply passes through the coils. This form, known as a single stroke bell, is suitable for signalling work, because every time the push is pressed a stroke is given.

Lifting Magnet.—A lifting magnet employed in the handling of all kinds of iron goods is an interesting application of the electro-magnet principle. The magnet illustrated in

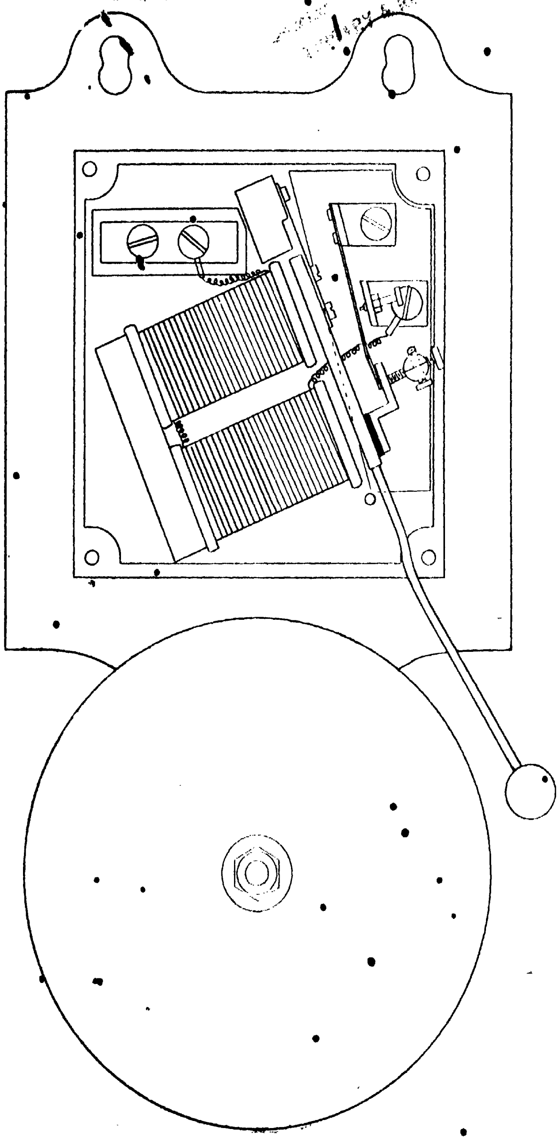


Fig. 12*a*. ARRANGEMENT OF TREMBLING BELL.

Fig. 13 is made by the Witton-Kramer Electric Tool and Hoist Co., and is intended for lifting pig iron, scrap iron, steel

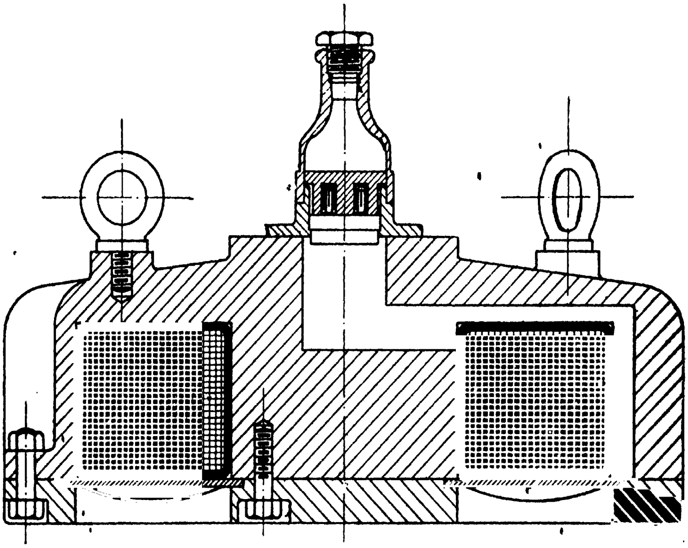


Fig. 13. SECTIONAL VIEW OF LIFTING MAGNET.

turnings, and similar material. The construction is shown by the figure, from which it will be seen that the essential features are the large circular coil and the surrounding shell, which is made of mild steel. The magnetising coil is wound with cotton-covered wire, and special means are taken to preserve the insulation from moisture. After winding, the coils are placed in a chamber and the air and moisture extracted by means of a pump. The coil is then impregnated with a bituminous compound. Below the coil is a shield of steel to protect the windings. Special care is taken with the leading-in wires, the slack lead being taken up by means of a spring drum. The magnet is hung from the crane chain.

As an example of the weight these magnets will lift, it may be stated that a magnet 36 inches in diameter, weighing itself 16 cwts., will lift 6 tons of pig iron or about 4 tons of scrap. To excite a magnet of this size the power required is about 3 kilowatts. The cost of these magnets is high, but the great saving in time and labour will in many cases justify their use.

EXAMPLES.

(1) Describe how you would use a magnetic needle or compass to detect which way a current was flowing in a wire in the following cases: (*a*) When the wire is running horizontally along under a ceiling; (*b*) when a wire is running horizontally on the surface of a wall; (*c*) when a wire is running vertically on the surface of a wall. Draw up a set of simple rules for the three cases. (C & G) (E).

(2) Make a sketch showing the distribution of the lines of force produced by a current flowing through (*a*) a coil consisting of a single turn, (*b*) a solenoid.

(3) Give a diagram of the essential parts of a trembling bell circuit, showing the direction of the current in the battery and windings, and the polarity produced thereby. Explain clearly how the bell acts. (C & G) (E).

(4) A U-shaped electro-magnet is provided with a magnetising coil on each limb. Explain the correct method of connecting the coils in series, and consider what would be the result of passing the current if the coils were incorrectly connected.

(5) Sketch the form and distribution of the lines of magnetic force in the field surrounding a long straight conductor which carries a current. Give a second sketch showing similarly the lines of force in the field of two parallel straight conductors carrying currents flowing in the same direction. (C & G) (E).

(6) Sketch approximately to scale, the magnetisation and permeability curves of wrought iron and cast iron. (C & G) (E).

CHAPTER V

MAGNETO-ELECTRIC INDUCTION

Production of an E.M.F.—In the previous chapter it was explained how, by means of an electric current, magnetism may be produced. Now the converse effect will be dealt with, viz., the production of an electric current by means of motion in a magnetic field.

It may be shown very simply by means of experiment, that if a conductor be moved through a magnetic field, there will be an E.M.F. produced in the conductor, provided that the direction of motion, the direction of the field, and the length of the

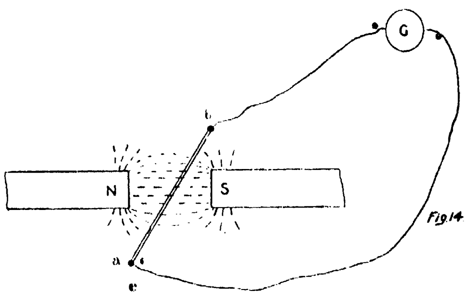


Fig. 14

conductor are perpendicular to each other or have components which are perpendicular. The honour of this discovery belongs to Faraday, who gave the name of *magneto-electric induction* to the phenomenon.

The method of carrying out the experiment will be understood on referring to Fig. 14. The conductor (*a b*), the ends of which are connected to a galvanometer or sensitive voltmeter,[1] G, is capable of being moved between the poles of the electromagnet. It is found that, when the conductor is moved in the

[1] Various types of voltmeter are described in chap. xiv. At this stage a galvanometer or voltmeter may be regarded as a detector of an electric current.

direction of its own length or parallel to the lines of force of the field, no effect is produced, and that the effect is a maximum when the conductor is moved across the field so as to *cut the lines of force.*

The law governing the production of an E.M.F. by magneto-electric induction is sometimes known as Faraday's law, and is as follows: The E.M.F. produced is proportional to the rate of cutting lines of force and, with the units chosen, is equal to the number of lines of force cut per second.

The E.M.F. obtained will be given in absolute C.G.S. units, and to express in volts it is necessary to divide by 10^8.

$$\text{Thus E.M.F. (volts)} = \frac{\text{rate of cutting lines}}{10^8}$$

The following rule, due to Fleming, is useful for determining the direction of the E.M.F., induced by moving a conductor through a magnetic field: hold the right hand so that the thumb and the first and second fingers are all at right angles to each other. Let the forefinger point in the direction of the lines of force and the thumb in the direction of motion of the conductor, then the out-stretched second finger will give the direction of the induced E.M.F. in the conductor.

There is another method of regarding magneto-electric induction which is sometimes more convenient than the one explained above. Suppose a coil of insulated wire, a solenoid for example, is taken, and its ends connected to the terminals of a galvanometer. When a small bar magnet is pushed into the coil there will be a deflection of the galvanometer pointer. On withdrawing the magnet, there will be a deflection in the opposite direction. Notice that so long as the magnet and coil remain relatively stationary, there is no effect; also, that when the south pole is advanced into the coil, the current flows round the coil in a clockwise direction, looking from the side at which the magnet enters. The following is a convenient rule for remembering the effects produced: considering the south pole, the relation between the direction of the current and the direction of motion of the pole is the same as that between the direction of rotation of a right-handed screw and the motion of the screw, *i.e.*, to advance it must be turned clockwise. In a similar way the north pole corresponds to a left-handed screw.

The E.M.F. produced is proportional to the rate of change of the number of lines threaded through the circuit. It is not difficult to see that this law (known as Maxwell's) is the same as that of Faraday.

Think of a magnet pole being pushed into a coil consisting of a single turn of wire. This is illustrated in Fig. 15. Under

the conditions shown in the diagram, a certain number of lines of force pass through the loop. A certain number do not. Each line of force issuing from the pole has to cut the conductor when being threaded into the coil. In other words, the rate of change of the number of lines threaded through the coil will be exactly the same as the rate of cutting lines. Thus the two methods of regarding magneto-electric induction are not dissimilar; the first, however, is more convenient when dealing with dynamos, the second when dealing with transformers.

Production of an E.M.F. by change of flux.—So far we have considered the production of an E.M.F. due to relative motion

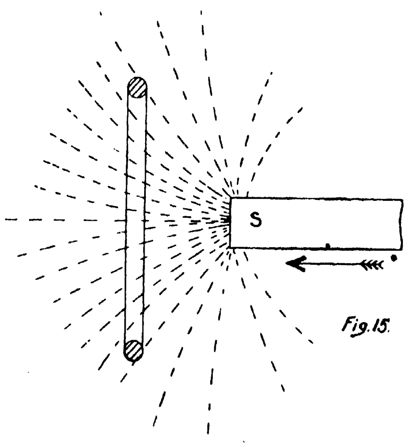


Fig. 15.

between a conductor and a magnet or a magnetic field. We shall now deal with a case in which, although there is a change in the flux threaded through a circuit, this change is not produced by mechanical motion. A and B, Fig. 16, are two coils of insulated wire. A is connected to a galvanometer, B is connected to a cell with a key in circuit. So long as no current flows through B there is no flux passing through it, nor is there any flux through A (neglecting the earth's field which is, of course, fixed). When the key K is closed a current will flow through B, and owing to the position of A, a number of the lines of force set up by the current in B will pass into A. Before the key was closed there was no flux in A. When the current has reached its final value there is a definite flux threaded through A. Obviously, then, there has been a

change in the flux of A, and therefore during that change an E.M.F. will have been produced.

Any student approaching this subject for the first time, should have the opportunity for carrying out experiments similar to the one described above. He should discover for himself, the relation between the current in the coil A (termed the secondary coil) and that in the primary coil, B, when the current is being started. The current flowing in the coil B, produced by the battery, is known as the inducing current; that produced in the coil A, is the induced current. The relation between the direction of the currents is as follows: when the current in the primary coil is growing that produced in the secondary coil is in the opposite direction

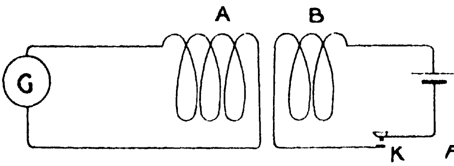


Fig. 16.

to it; when the current in the primary is dying away, the induced and inducing currents are in the same direction. These experiments illustrate the principle of the induction coil and transformer which will now be briefly described. In the induction coil, a current in the primary coil is started and stopped by some kind of automatic device. In the transformer, the primary current is known as an alternating current, and is always changing both in magnitude and direction.

The Induction Coil.—The purpose of an induction coil is to provide a current at high pressure, often for the purpose of producing sparks in air or discharges through vacuum tubes such as X-ray tubes. The primary and secondary coils are usually cylindrical — the primary being placed inside the secondary. The primary coil is wound with a few turns of thick cotton-covered copper wire; the secondary coil contains many turns of fine wire insulated with silk, and is wound in sections. Since the number of lines cut by each turn of the secondary coil is practically the same, it follows that the E.M.F. produced in the secondary winding may be increased almost indefinitely by increasing the number of turns of wire on that coil.

Fig 17 is a diagrammatic view of a type of induction coil, and Fig. 17*a* is a diagram of the connections. The current, which may be provided by a few accumulators, is led from the

terminals through the interrupter or break, B, to the primary coil. The secondary winding is not electrically connected with the primary at all. Passing through the primary winding is a core consisting of a bundle of iron wires or iron strips. The condenser[1] is connected across the gap of the interrupter, and serves to reduce the time which the spark lasts. The action of the interrupter is as follows: the current from the battery can pass round the primary winding when contact is made at B. The primary current magnetises the core and pulls up the iron armature A, thus causing the circuit to be broken. When this happens, the core loses its magnetism. The armature is pulled back by the springs and the contact

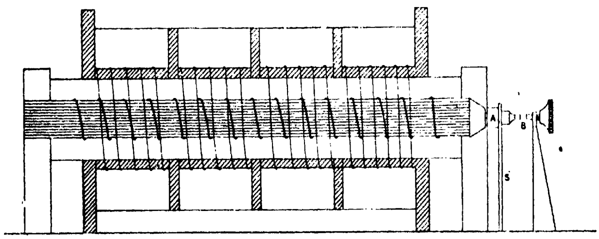


Fig. 17. DIAGRAMMATIC VIEW OF INDUCTION COIL.

is re-established. Thus a continuous vibration similar to that produced in a trembling bell is obtained. When the current is growing in the primary winding an E.M.F. is produced in the secondary in the opposite direction to the primary current. When the primary circuit is opened and the current is falling the E.M.F. produced in the secondary is in the same direction as the primary current. It might seem at first sight that the discharges produced in the secondary would be first in one direction and then in the other. As a matter of fact, however, the E.M.F. produced at "make" is very much smaller than that produced at "break." For many purposes the reverse discharge, as it is called, is undesirable, and special means are employed to reduce it. The precise action of the condenser is difficult to explain. It is sufficient here to state that if of suitable size, it hastens the stopping of the current, and therefore increases the voltage generated at "break."

The interrupter described here is the most common and

[1] A condenser is a device for storing electricity. In its most usual form it is built up from sheets of tinfoil separated by sheets of mica or paper soaked in paraffin wax. The sheets of tinfoil are called the plates of the condenser, and they are connected alternately to the positive and negative terminals. Fuller details will be found in books which deal with electrostatics.

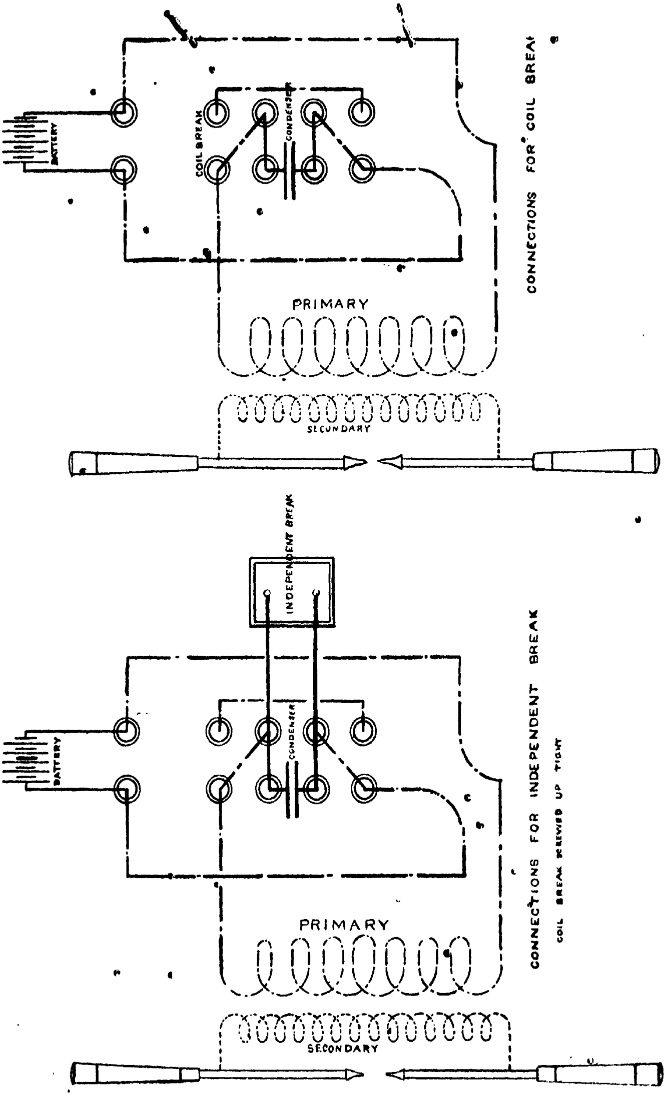


Fig. 17a. Diagram of Connections for Induction Coil.

perhaps the simplest, but other forms are used. The lower diagram of Fig. 17*a* shows how connection would be made to an independent break.

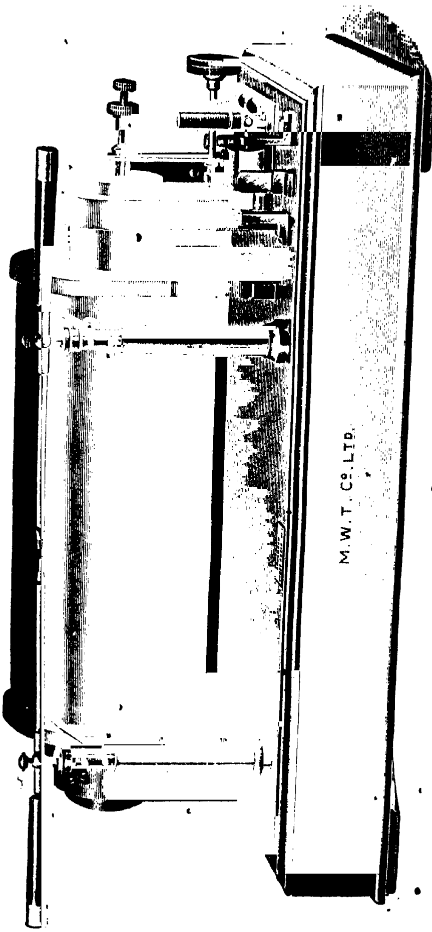


Fig. 18. View of Induction Coil manufactured by Marconi's Wireless Telegraph Co. Ltd.

Fig. 18 is an illustration of an induction coil manufactured by Marconi's Wireless Telegraph Co. Induction coils are employed nowadays for quite a variety of purposes. They are used for electro-medical work and for exciting

X-ray tubes. A large number of internal combustion engines employ some form of induction coil for producing the spark to ignite the mixture of gases. Induction coils may be used in wireless telegraphy for producing the oscillatory discharges in the transmitter.

Transformers. — The theory and mode of action of a transformer, or to use its full name, a statical transformer, can only be understood after the student has mastered the properties of alternating currents. But as the transformer illustrates the principles which have been explained at the commencement of this chapter, it may be worth while to give a general account of its construction. In a simple type of transformer there are two windings, the primary and the

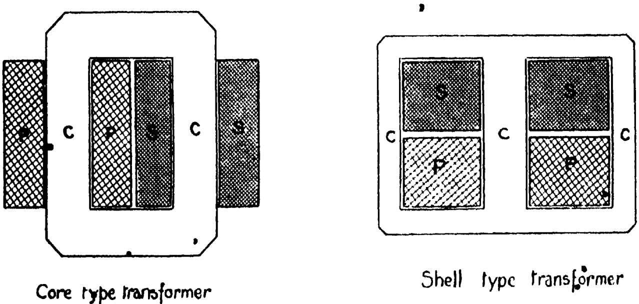


Fig. 19.

ARRANGEMENT OF CORE AND COILS IN TRANSFORMERS.

secondary. Both of these may be divided into two or more coils. Passing through both these windings is a core, forming, as a rule, a complete magnetic circuit for the flux. This core is built up of sheets of soft iron or mild steel, known as punchings or laminations. These are insulated from one another by thin sheets of tissue paper. In another pattern, known as the shell type, the windings pass through the laminations instead of laminations passing through the windings. Fig. 19 will explain the two patterns. Whatever construction is adopted, the primary winding is supplied with an alternating current, *i.e.*, a current which flows first in one direction and then in the other. An E.M.F. is generated in the secondary winding by the principle of magneto-electric induction. When there are the same numbers of turns on the primary and secondary windings, the E.M.F. generated in the secondary will be almost exactly equal to that supplied to the primary. If there are twice as many turns on the secondary as on the primary, the secondary E.M.F. will be

twice that of the primary, and so on. The ratio of the secondary to the primary voltage is known as the "ratio of transformation." When there are more turns on the secondary than the primary, it is called a "step-up" transformer. When the reverse is the case, it is called a "step-down" transformer. It is obviously possible to change from one to the other by using the secondary as the primary.

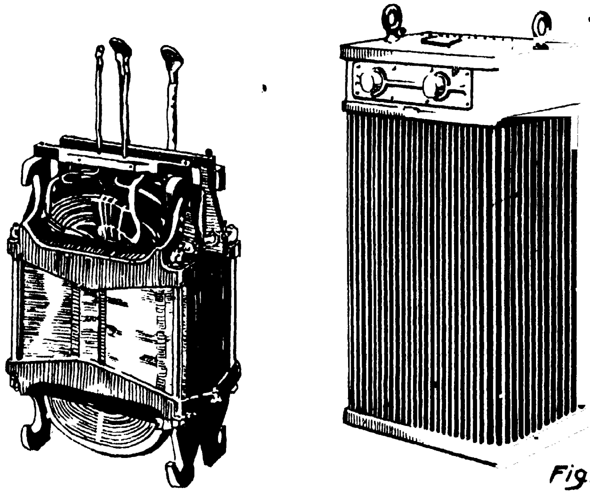


Fig 20.

VIEW OF WESTINGHOUSE TRANSFORMER.

The great importance of the alternating current transformer lies in the fact that it converts an alternating current from one voltage to another without rotating machinery and with very little loss of power. Fig. 20 shows a transformer made by the British Westinghouse Co. The transformer is of the shell type, and the primary and secondary windings are wound in sections and interleaved with each other. The whole is immersed in oil contained in a cast iron case.

EXAMPLES

(1) State Faraday's law of magneto-electric induction, and mention some application of it. If a conductor is moved through a magnetic field at a speed of 20 feet per minute, so as to cut the magnetic lines at an angle of 45°, calculate the E.M.F. produced per foot of conductor, assuming the induction in the field to be 10,000 lines per square inch.

(2) If the north-seeking end of a magnet be thrust into a coil of wire, the ends of which are joined together, what will be the result? Illustrate by means of a sketch. (C & G) (E).

(3) Describe the essential parts of an alternating-current transformer, and mention the object of the apparatus. State the approximate relations between (*a*) the primary and secondary pressure, and (*b*) the primary and secondary currents at full load. (C & G) (E).

(4) A rectangular coil 20 centimetres × 10 centimetres, consisting of 10 turns, is revolved through a uniform field at the rate of 600 revolutions per minute. Calculate (i) the maximum value, and (ii) the average value of the E.M.F. produced when rectified by a commutator.

(5) A conductor 6 inches long moves through a magnetic field of density 10,000 lines per square centimetre at the rate of 1000 feet per minute. Calculate the value of the induced E.M.F., the direction of motion, the length of the conductor and the field being at right angles.

(6) Two coils fit one inside the other, and one—the inner—has a steady current passing through it clockwise. When a piece of soft iron is plunged into the coils an E.M.F. is produced in the outer coil. Explain this, and find out the direction of the induced current, supposing the outer coil is short-circuited.

(7) A vertical conductor moving through a magnetic field from left to right generates an E.M.F. When the ends of the conductor are connected, a current flows which heats the conductor and the outside circuit. Show from the principle of work that a current flowing in the opposite direction tends to move the conductor from left to right.

(8) The flux in a transformer changes from zero to 1,000,000 lines in $\frac{1}{100}$ second. Calculate the average value of the E.M.F. produced in the secondary winding, supposing it to consist of 1000 turns. Assume that the flux embraces all the turns on the secondary winding.

CHAPTER VI

CONTINUOUS CURRENT MACHINES—THE ARMATURE

The Generation of an E.M.F.—The principle of magneto-electric induction explained in the previous chapter has its most important application in the theory and construction of dynamos. It has been explained that when a conductor moves through a magnetic field in such a direction as to cut the line of force, an E.M.F. will be produced in the conductor. This is accomplished in continuous current machines by revolving a set of conductors in a fixed magnetic field.

A rotary motion is adopted for mechanical reasons, no machine having been constructed with reciprocating motion.

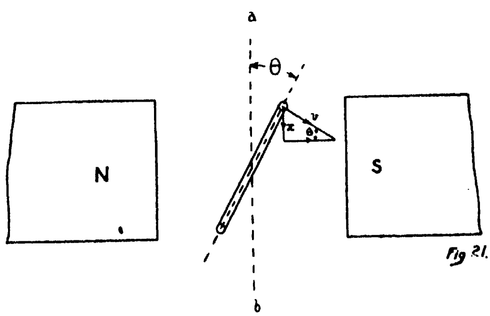


Fig 21.

Consider first of all the effect of revolving a rectangular coil in a uniform magnetic field at a uniform speed, the axis of revolution being at right angles to the direction of the field, Fig. 21. If such a coil be connected with a galvanometer and slowly revolved, it will be found that the galvanometer pointer oscillates about the zero. This indicates that the current generated flows through the galvanometer first in one direction and then in the other. We shall now seek the explanation of this. Let us assume that a coil starts from a position in which

its plane is vertical and perpendicular to the field. In this position, the sides of the coil are moving parallel to the field, and no part of the coil is cutting the lines of force. Next, consider what is happening when the coil has moved through 90° from the starting position. The conductors which form the sides of the coil are now moving perpendicularly to the field, and are therefore cutting the latter at the greatest possible rate. In the first position, the E.M.F. generated by the revolving coil was zero; in the present position, it has its maximum value. A little consideration will show that the E.M.F. will have continuously increased during this quarter revolution, because the E.M.F. depends upon the component of the motion perpendicular to the field. This will be proved below. In the meantime follow the course of events in the coil during one complete revolution. The E.M.F. having reached its maximum value at 90° will begin to decline, and at 180° from the start will again have reached zero. Further motion results in exactly the same sequence of changes, except that the E.M.F. generated by the coil will now be in the opposite direction. This is because any one part of the coil is, during the second half of the revolution, cutting the flux in the direction opposite to that of the first half. To sum up: the revolving coil is the seat of an E.M.F. which varies both in magnitude and direction; the consideration of one complete revolution (360°) is sufficient, because the second revolution will be an exact repetition of the first, and so on. One revolution will correspond to one complete cycle of changes. A simple coil revolving at a uniform speed generates an alternating E.M.F., and the current which this E.M.F. gives rise to, is called an alternating current. The revolving coil constitutes a simple type of alternating current dynamo or alternator.

Graphical Representation.—A method of representing this alternating current, which is of the greatest value, will now be described. Let $a\ b$, Fig. 21, be the plane from which the coil is supposed to commence its motion, the magnetic field being horizontal and the axis of rotation being at right angles to the plane of the paper. Consider the coil in such a position that its plane makes an angle θ with the axis $a\ b$, or, in other words, suppose the coil has revolved $\theta°$ from the start. The direction of motion is shown by the straight arrow, and the motion may be resolved into two motions at right angles; one parallel to the flux and the other perpendicular to it. The small figure shows the three motions and the angle between them. If v is the real velocity and x the vertical component

$$\frac{x}{v} = \sin\theta$$

$$\therefore x = v \sin\theta$$

Now the E.M.F. generated by the coil is proportional to x, because x represents the rate of cutting the flux. v is of course constant, and thus it follows that

$$\text{E.M.F. generated} \propto \sin \theta.$$

When $\theta = 0°$ or $180°$ or $360°$, $\sin \theta = 0$, and therefore the E.M.F. is zero.

When $\theta = 90°$ or $270°$, $\sin \theta$ has its maximum value ($= +$ or $- 1$), and therefore the E.M.F. is a maximum at these positions.

All who have some acquaintance with trigonometry will recall the method of representing the changes in the function of an angle by means of rectangular co-ordinates. In Fig. 22

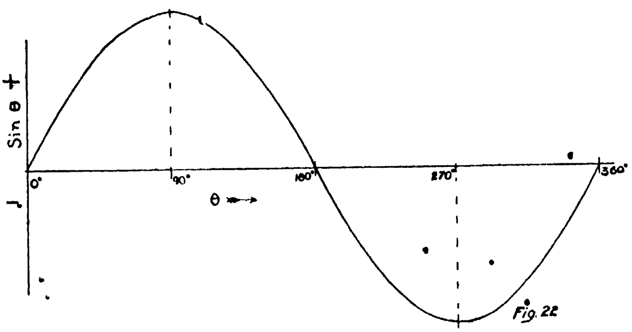


Fig. 22

a graph is given showing how the sine of an angle varies with the angle. It is simply a graph which has been plotted with angles as abscissæ and the sines of these angles as ordinates. Now, since a coil revolving at a constant velocity in a uniform field generates an E.M.F. which is proportional to the sine of the angle through which it has turned, this graph also represents, to a certain scale, the changes in E.M.F. during one complete cycle. In Fig. 22 the abscissæ represent the angle in degrees, and the ordinates represent the values of the sines corresponding to these angles. As the angle is proportional to time, and the sines proportional to the E.M.F. generated, a curve plotted to show the relation between voltage and time will be of similar form.

Principle of Commutation.—The results obtained by revolving a coil of wire in a magnetic field have been considered in detail, because with the exception of a small and unimportant class of machines known as homo-polar generators, every continuous current generator has an alternating E.M.F. produced in its conductors. The manner in which this is made to produce a

continuous current will now be explained. The revolving coil shown in Fig. 21 was supposed to be connected to a galvanometer by means of flexible leads. An alternative method would have been to connect the ends of the coil to a pair of slip rings,

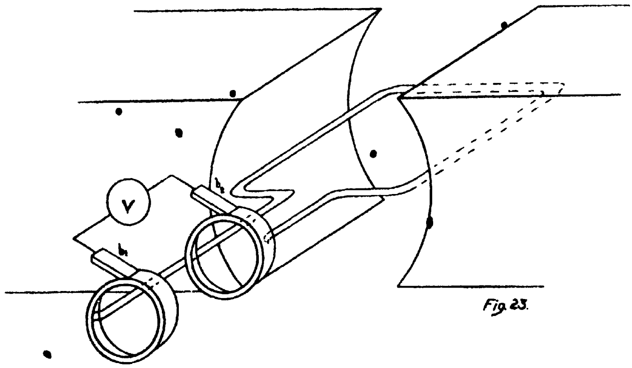


Fig. 23.

which revolving with the coil and being in electrical contact with the two fixed pieces b_1 and b_2 would produce the same result (Fig. 23). This is the method of leading out the current

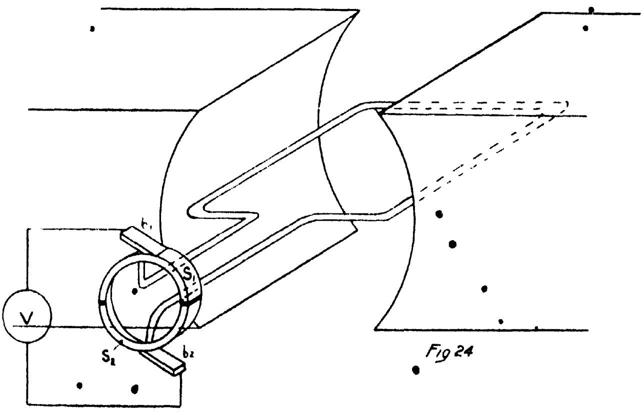


Fig 24

in an alternator with a revolving armature, and the fixed contacts are called brushes.

It may now be supposed that instead of the ends of the coil being connected to two slip rings, they are connected to the two halves of a divided ring as shown in Fig. 24.

The two halves of this ring S_1 and S_2 are insulated from each other and mounted so as to revolve with the coil. Two fixed brushes b_1 and b_2 make contact with S_1 and S_2 in turn. The difference between this method of connection and the previous arrangement will be clear. Whereas with the slip rings, one brush, b_1 for instance, is always in contact with the same conductor, with the present arrangement a brush is always in contact with a conductor undergoing the same treatment. For example, b_1 is always connected to a conductor moving in front of the north pole. Thus although the E.M.F. impressed on the brushes varies from zero to a maximum, and down to zero again, it never changes sign, and therefore current obtained from such a machine will always flow in the same direction. The changes in E.M.F. are as shown graphically by the curve B in Fig. 25.

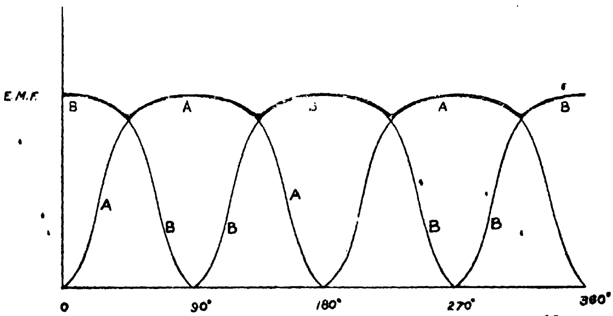


Fig 25

The two halves of the divided ring form the two segments of a *commutator*. Suppose now that a second similar coil is mounted on the shaft with its plane at right angles to the first coil, and that the ends of it are connected to another pair of segments placed between the first pair. The second coil will generate a varying E.M.F. of the same magnitude as the first, but the maximum E.M.F. will occur a quarter of a revolution (or 90°) later. This is represented by the line A in Fig. 25. The thick black line shows the P.D. between the brushes. Notice that the changes in the E.M.F. are now very much smaller and of higher frequency.

By considering four and then eight coils to take the place of the two shown here, it will readily be understood that it is possible to obtain from a machine with a large number of coils, an E.M.F. which varies very little. In fact, with an actual machine built in this way, the variations could only be detected

with the most sensitive of instruments. The assemblage of coils is called an *armature*, and when the coils are not electrically connected inside the armature, as in this case, it is termed an open coil armature. This type of armature, although useful to show the theory of the commutator, is not now used in practice, but has given place to armatures of the closed circuit type.

The Ring Armature.—Of armatures with closed circuits, the simple ring or Gramme winding is the most easily understood. In the diagram on p. 53 no support is shown for the revolving coil. Actually, as will be explained in the next chapter, the

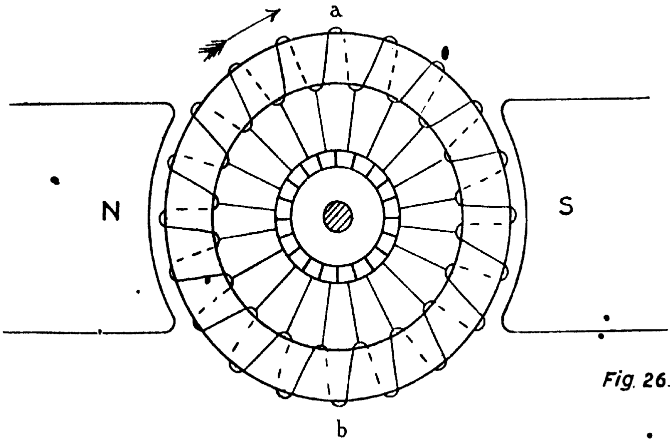


Fig. 26.

coils would be wound on a core made of soft iron stampings which with this form of winding might be mounted directly on the shaft. With the ring armature the core must be made hollow, and a coil of rectangular section is formed by winding insulated wire round the ring. Fig. 26 will make this clear. The winding in this case may be continuous, and the conductors equally spaced round the armature.

The distribution of the flux in the ring armature is important and for a machine with two poles is shown in Fig. 27. Notice that very few lines pass through the interior of the ring. With this type of winding only the portion of the coil lying on the outside of the armature is effective in producing a useful E.M.F., and indeed, any E.M.F., generated by the conductors on the inside of the core, will be opposed to that generated by the conductors on the outside, and will therefore reduce the voltage of the machine.

Let Fleming's rule now be applied to determine the direction of the E.M.F. produced. Consider, first, the conductors on the left hand side of the armature. Since the armature is rotating in a clockwise direction, these are moving up in front of the north pole, and the rule tells us that the E.M.F. will have a direction away from us. All the conductors coming at the moment under the influence of the north pole will tend to send a current flowing spirally up the armature. Next consider the conductors on the right hand side. These are moving down in front of the south pole, and tend to send a current round the

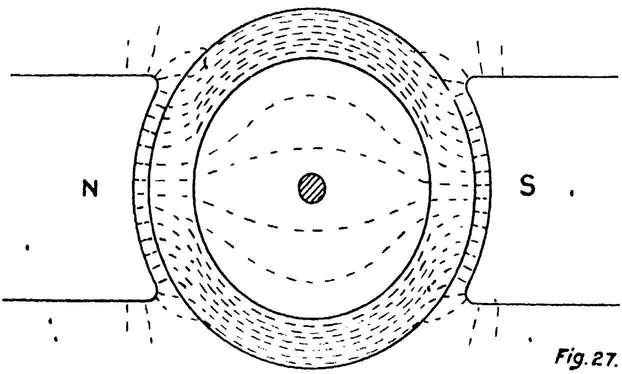


Fig. 27.

armature also in an upward direction. By symmetry, these E.M.F.'s will balance and no current will flow. The right and left hand sides of the armature behave like two batteries of cells connected in parallel.

Calculation of E.M.F.—The maximum difference of potential occurs between the two points *a* and *b*, and the collecting devices must be placed here in order to lead the current away. The P.D. between *a* and *b* is due to half the conductors on the armature, connected in series and may be calculated as follows:—

Let Z = the number of lines of force passing from either pole into the armature,

n = rate of rotation in revolutions per second, then

$\frac{1}{n}$ = time of one revolution,

N = total number of inductors, *i.e.*, the number of wires on the outside of the armature,

then average E.M.F. induced in one inductor = number of lines cut per second $= \frac{Z}{\frac{1}{2n}} = 2Zn$

since a conductor cuts all the lines in the time of half a revolution. Now $\frac{N}{2}$ conductors are in series; therefore

$$\text{E.M.F.} = \frac{N}{2} \times 2\,Z\,n = N\,Z\,n \text{ C.G.S. units}$$

$$E = \frac{N\,Z\,n}{10^8} \text{ volts}$$

This simple expression gives the voltage developed in any form of bi-polar armature and should be remembered.

The current which is led out from the armature at *a* and in again at *b*, divides in passing through the armature, so that the current in any conductor is only half that given by the machine.

The Drum Armature—Lap winding.—It remains for us to consider another type of closed circuit winding, known as the drum winding. This is similar to the one described in that the winding forms a simple closed circuit, but it is disposed differently upon the armature core. No conductors pass through the interior, and all conductors parallel to the shaft are the seat of an E.M.F.

Consider one of the coils of the armature shown in Fig. 26 for a moment. The coil consists of, first, the active part on the outside, second, the idle part on the inside, and third, the end connections. Suppose the wire to be taken from inside the core, and placed on the outside almost diametrically opposite, the end connections being lengthened to admit of this. What would be the effect? In the first place the E.M.F. generated by the new outside conductor will tend to send current round the armature in the same direction as the other active part of the coil, so that the E.M.F. of this particular coil will be doubled. Secondly, the amount of idle wire has been increased. If this process be carried out for all the coils on the armature, a winding will be obtained similar to that shown in Fig. 28, which represents a portion of the winding of a 2-pole lap wound drum armature. The conductors are shown numbered 1 to 40.

Notice that a front connection passes over 19 other conductors, or in passing across the front of the armature 19 must be added. Similarly, in passing back behind, 17 must be

subtracted. These numbers 19 and 17 are called the front and back pitches respectively.

Wave Winding.—There is another kind of drum winding which is quite different from the above. Imagine an armature with the same number of conductors as the last one described, and suppose the end connections are made as follows: from 1 connect to 20, and instead of connecting from 20 back to 3 connect forward to 39, from 39 to 18, 18 to 37, 37 to 16, and

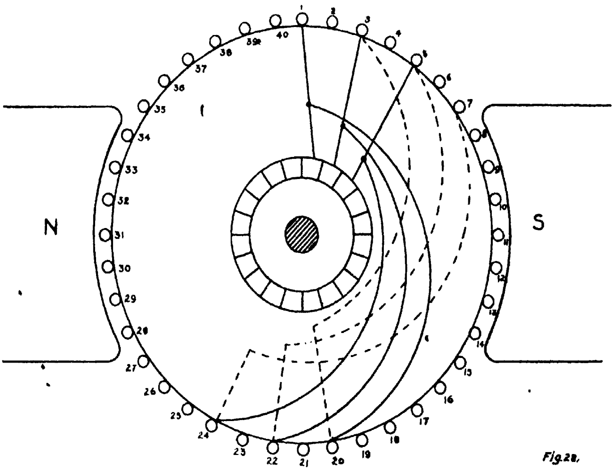


Fig. 29.

so on, adding on 19 both for front and back connections. This is shown in Fig. 29. A table giving the numbers of the conductors will be as follows:—

1—20—39—18—37—16—35—14—33—12—31—10—29—8—27—6—25—4—23—2—21—40—19—38—17—36—15—34—13—32—11—30—9—28—7—26—5—24—3—22—1.

After passing through all conductors, we return to the starting point, and moreover, there are no conductors on the armature to which connection has not been made. This type of winding is known as wave winding.

Former Wound Armatures. — Most modern continuous current dynamos and motors are provided with drum armatures. The simple windings just considered had only 40 conductors. In order to generate a sufficiently high E.M.F. many more are required, and they are often arranged somewhat differently.

In the winding table given above we passed from conductor 1 to conductor 20 and then back to conductor 3. Suppose that the numbers in Fig. 28 refer, not to conductors, but to slots in the armature core, each slot holding a number of conductors, then the winding may be carrried out as follows: starting from a conductor in slot 1, we pass to one in slot 20, then back to a second conductor in slot 1, then to another conductor in slot 20. If this operation be repeated 10 times, a winding will be obtained with 10 conductors in each slot. When all the conductors in slot 20 have been

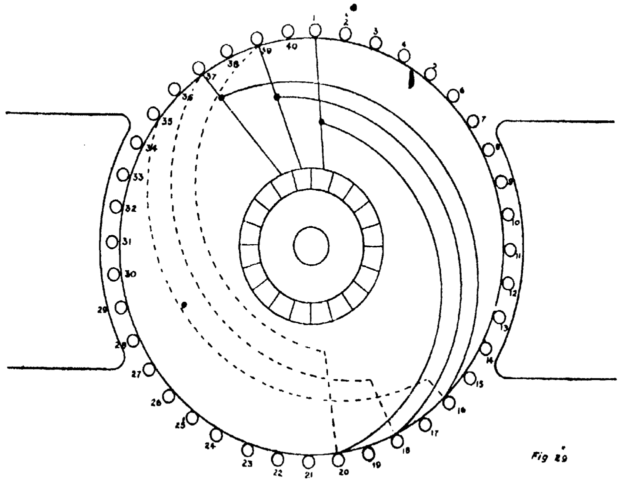


Fig 29

connected, then, and not till then, we pass to a conductor in slot 3. The conductors in slots 1 and 20 and the end connections between them, form a coil which may be wound on a former, taped, and then put into the slots. Such an armature is said to be "former wound," and the cheaper construction which is thus obtained, is the chief reason for its adoption in commercial machines.

Multipolar Armatures. — Up to the present, armatures intended for machines with only one pair of poles have been considered, because they are the simplest. Most modern machines are provided, except in the case of small sizes, with 4, 6, 8, or more poles, the number increasing in general with the output of the machine. In the case of ring armatures, the winding may be the same, however many poles there are, the difference being in the position and number of the

collecting points. With drum armatures this is not the case, since a conductor has to be connected across the armature to one under the influence of a pole of the opposite kind. Thus, with a 4-pole machine, the connections have approximately to bridge across 90°, with an 8-pole machine, across 45°, and so on. For further consideration of armature windings the reader is referred to larger works.

EXAMPLES

(1) Make a diagrammatic sketch of a shunt-wound continuous current dynamo with ring armature, and indicate clearly the direction of flow of the current in each part of the machine. (C & G) (E).

(2) Describe with the aid of a sketch the construction of a ring armature. Why is it important that the flux entering the interior of the core should be small?

(3) A ring armature contains 24 conductors on its surface. Show how to convert it into a drum armature by taking the conductors from the interior of the core and placing them on the periphery. Make a table showing the arrangement of the winding which will be produced.

(4) The drum armature of a 2-pole machine is wound with 2,300 conductors and revolves at 1,200 revolutions per minute. The flux entering the armature is 0.5×10^6 lines. Calculate the E.M.F. developed.

CHAPTER VII

CONTINUOUS CURRENT MACHINES—MECHANICAL CONSTRUCTION

WE have seen in the previous chapters that it is necessary to produce a magnetic field in the armature of a continuous current machine. Except in machines of small size, this is done by means of electro-magnets, which are usually excited with current obtained from the machine itself. The magnet system used in such machines may have 2, 4, or any even number of poles—the larger the machine, the larger will be the number as a rule. In Fig. 30 is shown the arrangement of the field system for a machine with 2 poles. Fig. 31 shows a portion of the magnetic circuit for a 6-pole machine. The construction shown in this diagram is the one usually adopted in modern machines, the diameter of the yoke increasing with the number of poles.

The Magnetic Circuit. — The path through which the magnetic lines pass is known as the magnetic circuit, and it is necessarily of complex character. It may be considered as made up of the following component parts:—

(1) *The Armature Core, A.*—This is always built up of stampings of soft iron which are mounted with their planes perpendicular to the axis of rotation. The stampings, or core plates as they are called, are insulated from one another with thin tissue paper which is usually pasted upon them before they are punched. When the core is assembled the insulation forms about 10 per cent. of the armature length. The thickness of the plates is usually about $\frac{1}{40}$ inch.

The reason for building up the armature core out of plates instead of making it of solid iron, is to reduce the large currents which would otherwise flow round the core and cause heating and waste of energy. These are known as "eddy currents." Just as an E.M.F. is produced in a conductor placed near the surface of the armature, so an E.M.F. of equal magnitude would be produced in the face of the armature core, if this were made of solid iron. This E.M.F. would have a maximum value in

those parts of the armature, which at any instant are moving under a pole, and would fall to zero at parts midway between the poles, and also at the centre of the armature. Thus there is a tendency for currents to be set up in the core, but by interposing insulating material at intervals, a high resistance is introduced in the direction in which the currents tends to flow.

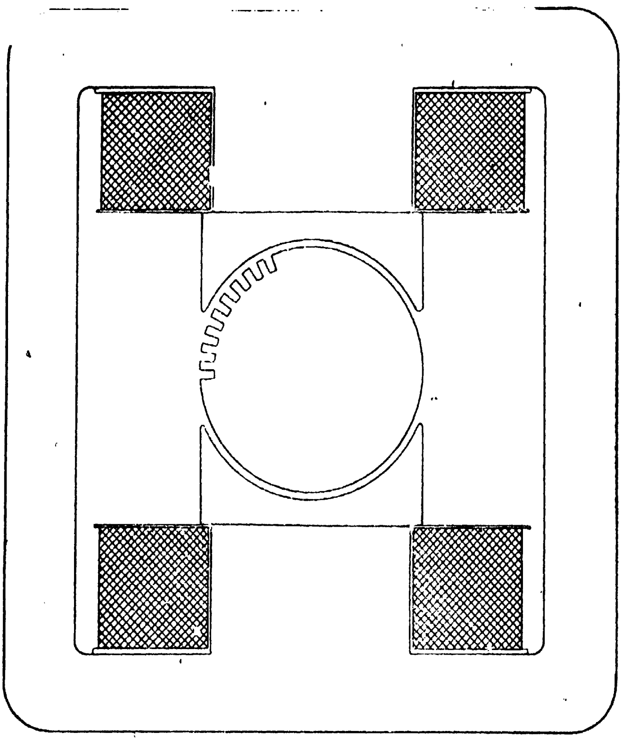


Fig. 30.

ARRANGEMENT OF MAGNETIC CIRCUIT IN BIPOLAR MACHINE.

It will be noticed that the armature is laminated in such a way that the lamination does not interfere with the path of the lines of force.

The loss of power due to eddy currents may be shown to be proportional to the square of the thickness of the plates. It is not advisable to reduce their thickness below 0.025 inch, because, although the decrease in eddy current losses would be

a gain, the increased cost of assembling and the greater space taken up by insulation would outweigh this advantage.

In modern armatures, the conductors or coils are always placed in slots, and such an armature is said to be "slotted." An alternative plan is to have the armature core smooth and place the windings on the outside of it. This was formerly the common practice, but the difficulty of keeping the conductors in position, and other reasons which cannot be entered into here, have caused the method to become obsolete.

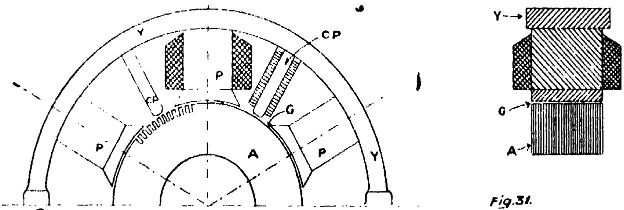


Fig. 31.

ARRANGEMENT OF MAGNETIC CIRCUIT IN MULTIPOLAR MACHINE.

(2) *The Air Gap, G.*—The clearance between the armature and the face of the pole is termed the air gap. The length of this gap varies from 0.05 inch to 0.2 inch in modern machines which have inter-poles; for machines without inter-poles, it is greater. Although the gap is so short compared with the other parts of the magnetic circuit, as many ampere-turns are required in many cases to drive the magnetic lines across it as through the rest of the magnetic circuit.

(3) *The Poles, P.*—The portions of the magnet system upon which the magnetising coils are wound, are termed the poles or pole cores. In most machines there is an enlargement at the end of the poles (placed in position after the coils are slipped on) known as the "pole shoe." The object is to decrease the flux density in the air gap. The poles are usually made of cast steel. Poles may be round, square, or elliptical.

(4) *The Commutation Poles, C.P.*—Situated between the main poles are the commutation poles or inter-poles. These are much smaller in cross-sectional area than the main poles, and as will be explained later, their function is chiefly to neutralise the magnetic effect of the currents flowing in the armature. Although absent from some dynamos, they are provided in most modern machines, as they increase the output for a given weight.

(5) *The Yoke, Y.*—The remaining part of the system is the yoke. Often a circular pattern is adopted as this gives a neat

appearance. Either cast iron or cast steel may be used for the yoke. Cast steel gives a lighter machine since a higher flux density may be chosen, and thus the cross-sectional area required to carry a given flux is smaller.

The Field Coils.—The magnetising coils are usually one on each pole, though there are a few bipolar machines with only one coil. The method of obtaining the magnetising current will be dealt with in the next chapter. When the magnetising current is small a round wire is used, for larger sections a strip of square or rectangular section is more economical in space. The wire or strip is insulated with a double layer of cotton, and the coils wound on a former, made either of metal, zinc for example, or insulating material. The coils after being wound are varnished and stoved (*i.e.*, heated in an oven) before being placed on the machine. The object of varnishing is to keep out moisture, since cotton is exceedingly hygroscopic and loses its insulating properties when damp. For carrying very large currents, such as will be the case with the series coils of compound machines, copper strip wound on edge is suitable. The depth of the winding on field coils varies from 1 inch in small machines to about 3 inches in large ones. Thin coils have the advantage of presenting a large radiating surface, and sometimes gaps are left in the winding to increase the cooling effect.

It may be remarked in passing, that all the energy supplied to magnetise the field system is spent in heating the coils. This heat is carried away partly by air currents and partly by conduction through the poles. The inner layers of the winding are always at a higher temperature than the outer ones, and deep windings are avoided since the inner layers of a deep winding are liable to be overheated.

The Armature.—Turning now to the armature, the method of driving the core is illustrated in Fig. 32. For drum armatures the spider, S, is made of cast iron, while for ring armatures some other material, such as gun metal, must be used to reduce as much as possible the flux passing into the interior of the ring. There are also provided two stiff end plates, which, when drawn together by bolts passing through the core, hold the core plates in position.

The cores of all modern armatures are provided with slots, the coils or conductors being mounted in the slots, which are lined with insulating material, such as micanite.

The Commutator.—For practical reasons the current cannot be led away from the revolving armature by stationary contacts pressing on to the conductors themselves. The outside circuit is connected with the conductors through the commutator, the segments of which are connected to the armature conductors at

regular intervals as already explained. Thus in a ring winding there may be as many segments on the commutator as there are coils on the armature, in which case every armature coil is connected between two neighbouring segments, or there may

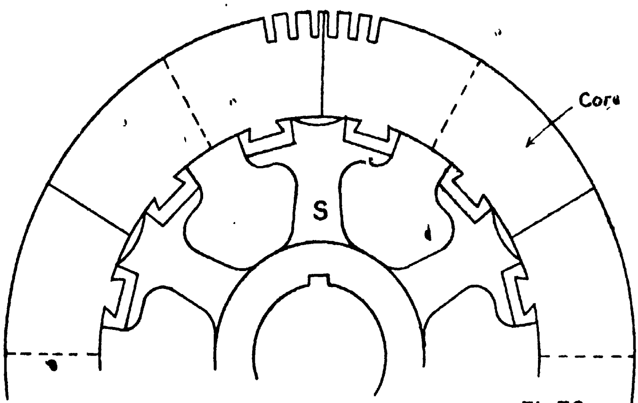


Fig 32

be two or three or any number of coils per segment. So long as there are the same number of coils between each pair, the machine will work satisfactorily, and, in general, the larger the

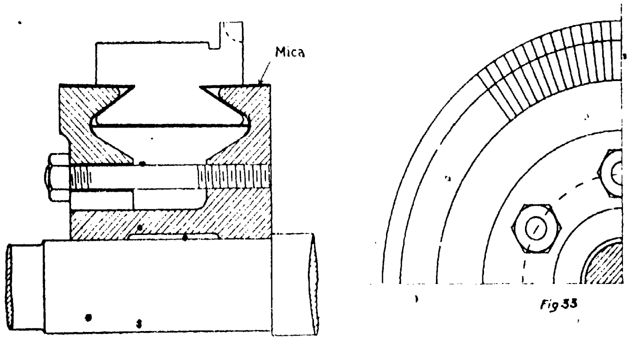


Fig 33

number of segments the more easy will it become to collect the current without sparking.

Commutators are built up of segments of hard copper insulated from each other by mica or micanite. Fig. 33 shows a commutator. A radial depth of not less than 1 inch

is usually allowed to admit of turning up from time to time. The method of holding the segments together will be understood from the drawing.

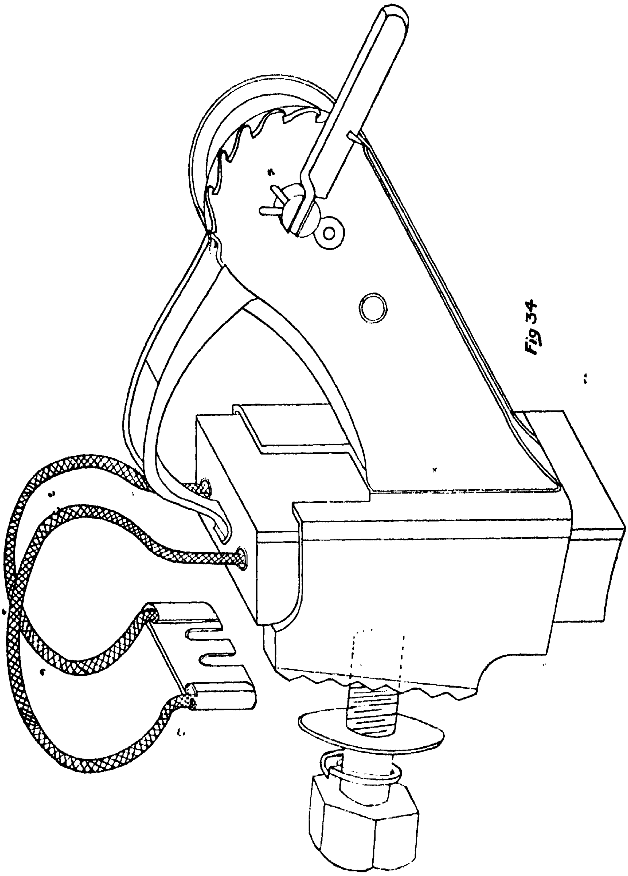


Fig 34

The Brushes.—The stationary contacts which press down upon the commutator are called the brushes. The name is derived from the circumstance that early types were made of wires bound together at the top and loose at the part where they touched the commutator. Except in a few cases the brushes in modern machines are blocks of carbon which are

pressed down on to the commutator by springs. Brushes of copper gauze made into a chisel shape are still occasionally used, especially in high speed machines. The receptacle for holding the brush is called the brush holder, and this must be so arranged that while allowing a movement of the brush in a radial direction, there is no possibility of "chattering."

A modern type of brush holder for use with a carbon brush is illustrated in Fig. 34.

The student should examine as many types of brush holders as is possible, a careful inspection being more instructive than pages of description. Those holders in which only the brush moves are preferred nowadays, and are termed box pattern. With carbon brushes, the current should be led into the brush by a flexible connection, usually made of copper wire plaited (sometimes called a pigtail connection) screwed on to the brush itself.

In most dynamos and some motors the brushes are mounted upon a rocker, the object of which is to permit of a rotary motion about the axis of the machine. For large machines, a hand-wheel working a worm and worm wheel is used, in order to get a delicate adjustment.

EXAMPLES

(1) Why is it necessary to laminate the iron core of a dynamo? Show by means of sketches, in which direction you would laminate the core (*a*) of a flat ring armature in which the magnet poles were presented to the sides of the ring; (*b*) in a cylinder armature in which the magnets were presented to the cylinder surface. (C & G) (E).

(2) What is the effect of sinking the wire into a slot in the laminated iron core of a D.C. armature? Give reasons for your answer. (C & G) (E).

(3) In what case and for what reason is it important that electro-magnets should have laminated cores? Is the position of the plane of lamination with respect to the axis of magnetisation important?

(4) What materials are employed in the construction of C.C. armatures? State the purpose of each of the materials you name.

CHAPTER VIII

CONTINUOUS CURRENT MACHINES—METHOD OF EXCITATION AND CHARACTERISTICS

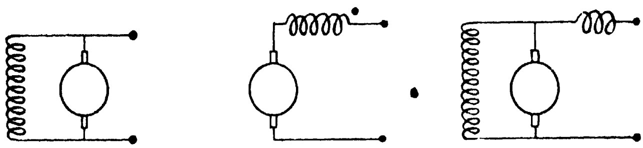
METHODS of Excitation.—A dynamo in which the magnetism is provided by permanent magnets is termed a magneto. The method is only used for machines of small power, since it is not possible to obtain a strong magnetic field without using electro-magnets. Magnetos are used for ringing up in telephone work, for firing the mixture of air and gas in internal combustion engines, and occasionally for other purposes.

Dynamos which are provided with electro-magnets may be divided into two classes, according to whether the current to excite the magnets[1] is obtained from the machine itself or from another source. The former class is termed "self-excited," the latter "separately-excited." As a rule, continuous current dynamos are worked self-excited, since they are then self-contained. With a separately-excited machine it is theoretically immaterial what strength of exciting current is used, and how many turns there are upon the winding, so long as the necessary ampere-turns are produced. In practice, it is usually convenient to use a small current and a large number of turns owing to the greater ease of regulating by means of a rheostat. In self-excited machines the magnetising current is obtained from the armature of the machine itself. The diagrams in Fig. 35 show three possible ways of doing this.

If the field winding be connected in series with the armature so that the magnetising current is the whole current given by the machine in the case of a dynamo, or supplied to the machine in the case of a motor, the machine is said to be "series wound" (*b*). When the magnetising coils form a separate circuit connected in parallel with the armature, the machine is "shunt wound" (*a*). Finally, when two windings are provided, and we have a combination of these methods, the machine is "compound wound" (*c*). In machines which have commutation poles

[1] The main poles are here referred to.

the latter must of necessity be magnetised by series windings. As regards the compound method, in the case of a dynamo, the windings are arranged so that both shunt and series turns magnetise the field system in the same direction, or, in other words, the action of the series turns is to strengthen the field produced by the shunt winding. With motors, an alternative arrangement is possible, in which the series winding is opposed to the shunt, the arrangement being known as "differential." The method has been adopted when a very constant speed is required, but is rarely used.



(a) SHUNT (b) SERIES (c) COMPOUND

Fig. 35.

Characteristics.—We shall now consider the results obtained from exciting a dynamo by the various methods described above, reserving the consideration in the case of motors for the next chapter. Whatever kind of electrical generator is used for supplying us with current, it is of importance to know how the P.D. which the generator supplies, varies with the amount of current taken from the it.[1] For example, think of a battery supplying current to a group of lamps connected in parallel. If the P.D. across the terminals of the battery be measured, first, when it is sending no current, and then when 1, 2, 3, 4, etc., lamps are connected to it, it will be found that as each lamp is added, the reading on the voltmeter is decreased.

If the internal resistance of the battery be known, the difference of potential between the terminals corresponding to any valve of current may be calculated.

Calling the terminal P.D., V, and E.M.F., E,

$$E - V = Cr \text{ where } r = \text{internal resistance of battery,}$$
$$\therefore V = E - Cr$$

Suppose a graph be plotted showing the relation between the terminal P.D. of the battery and the current taken from it, a result will be obtained as shown in Fig. 36. For any current

[1] A common error which beginners make is to suppose that the current obtained from a generator, a battery for example, is constant, and that when a second lamp is added in parallel with one already connected the two lamps simply share the current between them.

such as C, the portion *ab* represents the P.D. across the terminals, and the portion *bc* the "drop" inside the battery. Provided the E.M.F. of the battery remains constant, the sum of these voltages is constant, and since *bc* is proportional to current, the graph is a straight line. This graph, connecting terminal P.D. and current, may be termed the characteristic curve of the battery.

Separately-excited Machines.—Now think of the case of a separately-excited dynamo. Suppose the current through the field windings to remain constant, then the flux in the armature

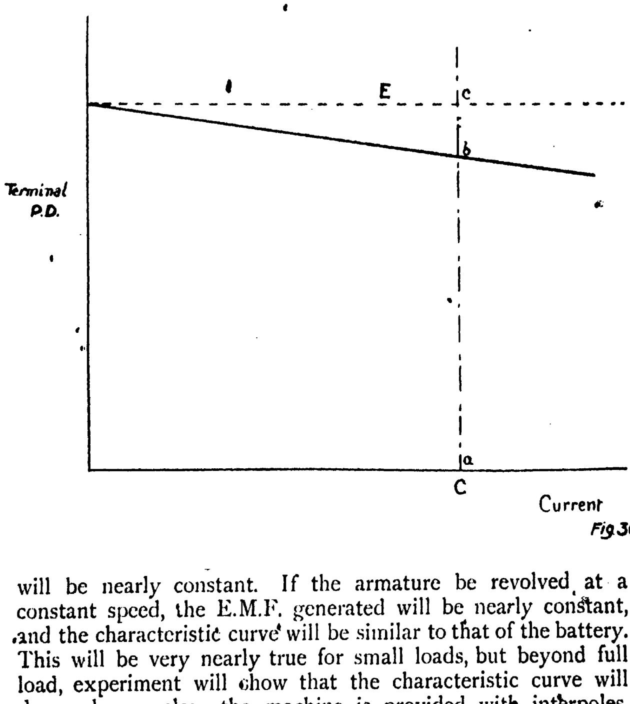


Fig. 36

will be nearly constant. If the armature be revolved at a constant speed, the E.M.F. generated will be nearly constant, and the characteristic curve will be similar to that of the battery. This will be very nearly true for small loads, but beyond full load, experiment will show that the characteristic curve will droop down unless the machine is provided with interpoles. To understand the cause of this it will be necessary to examine more closely the action of the currents flowing in the armature. Considering the case of a two-pole machine, it has been shown that the positions of the collecting points necessary to obtain maximum P.D. were at the ends of a diameter, at right angles to the direction of the flux. With the brushes in

this position, the distribution of current in the armature is symmetrical about the vertical axis, and the current flowing round the armature will be found to exert a magnetising action perpendicular to the direction in which the armature is magnetised by the poles. There are now two magnetising forces acting in the armature—the original effect due to the poles, H_1, Fig. 37 (*a*), and the smaller and variable effect due to the armature current H_2. Consequently, the direction of

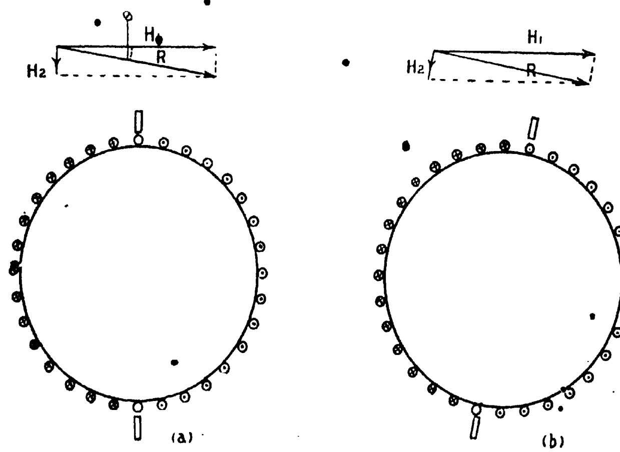


Fig. 37.

magnetisation is as shown in Fig. 37 (*a*), where R represents the resultant. Thus the currents flowing through the armature *react* on the magnetic field which produces them, and change the direction of magnetisation. In the case of a dynamo, the field has rotated in the same direction as that in which the machine is revolving, by the angle θ, and the neutral axis will be moved forward by the same amount. The consequence is, that if it is desired to keep the brushes in the neutral position, they must be set at an angle to the vertical, the value of which will depend upon the current taken from the machine. This is the reason for mounting the brushes on a rocker as described in chapter vii.

It will be noticed that the flux produced by H_2 will not give rise to a P.D. between the brushes, and it follows that if the brushes be always kept in the vertical position, the E.M.F. generated by the machine will remain constant. If, however, the brushes be moved forward so as to keep them in the neutral axis, Fig. 37 (*b*), it will be seen that the resultant R is less than

H_1, and therefore the generated E.M.F. will be decreased. As a matter of fact, it is usual in the case of a dynamo to move the brushes to a position in advance of the neutral axis, because this will be found to give the position in which there is the least sparking. This means that the angle between H_1 and H_2 will be still further increased, and therefore R becomes less, and the component of R at right angles to the line joining the brushes less still. Thus for large values of current in the armature, the decrease in terminal voltage will be greater than is accounted for by armature resistance, and the curve will droop. *See* Fig. 38*a*.

Shunt Wound Machine.—Consider now the case of a self-excited machine with shunt windings connected directly across the brushes. In addition to armature resistance and armature reaction, there is a third reason for the terminal P.D. decreasing as load increases. This is due to the fact, that as the current through the field windings is proportional to the terminal voltage of the machine, a decrease in voltage across the brushes leads to a corresponding decrease in magnetising current. Although the reduction in field strength will not be proportional to the reduction of the current, this causes the characteristic curve to droop still further, as in Fig. 38*a*.

In actual working, both shunt and separately-excited dynamos are provided with a regulating rheostat, the resistance of which is decreased as the load increases, and by hand regulation in this way, the voltage at the terminals may be maintained constant at all loads.

Series and Compound Wound Machines.—In the case of series wound machines the gauge of wire must be such that the full load current of the machine may be passed through the field winding without causing overheating. Series windings are rarely, if ever, used by themselves for dynamos, but machines provided with both shunt and series coils are common, and it will be worth while to consider the shape of the characteristic curve due to a series winding alone. The magnetising current being identical with the load current, it follows that at no load, the E.M.F. generated by a series machine will be due to the residual magnetism of the poles. It is interesting to notice that no self-excited machine can possibly work, unless a certain amount of magnetism remains in the field system when the machine is stopped. Moreover, the connections must be made in such a way that any current sent round the field coils by the machine will strengthen the poles and increase the flux in the armature; otherwise the machine will not "build up." Referring to the series curve in Fig. 38*b*, the point at zero load represents the E.M.F. produced by the residual magnetism

alone. If the external circuit be closed, this E.M.F. will send a current which will increase the magnetic flux passing into the armature, and therefore raise the E.M.F. The larger the current the more ampere-turns will be produced, and the greater

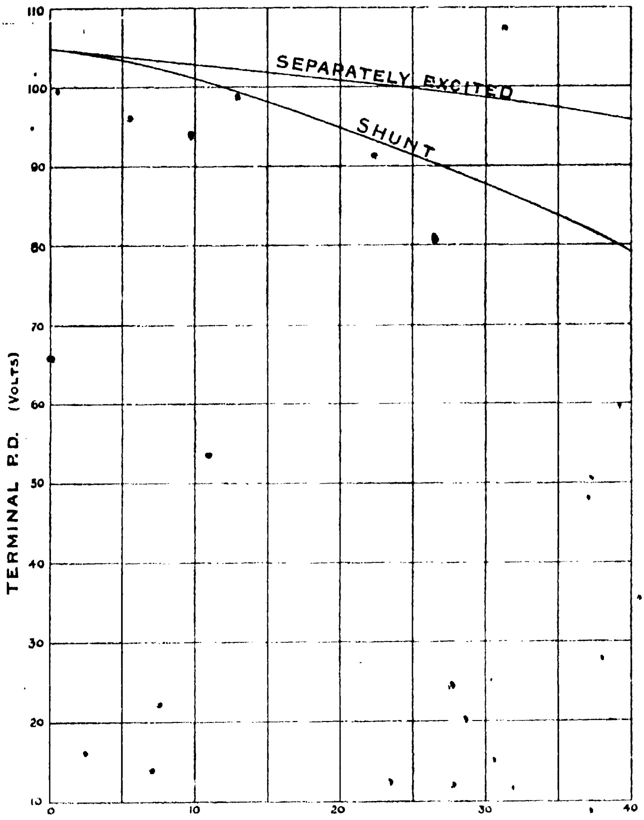


Fig. 38A. LOAD CHARACTERISTIC FOR SAME MACHINE, SEPARATELY-EXCITED AND SELF-EXCITED (SHUNT).

the voltage generated. Although the flux will not increase proportionately with the load current, the curve would continue to rise indefinitely if we were considering the E.M.F. generated.

The P.D. at the terminals, however, is less than the E.M.F. by the internal drop. At about 80 amperes the curve becomes

horizontal, and here the increase in drop due to an increase in current balances the increase in E.M.F. Beyond this point the effects of armature resistance and reaction cause the curve to droop as for a separately-excited machine. It will be seen from these considerations that the series machine

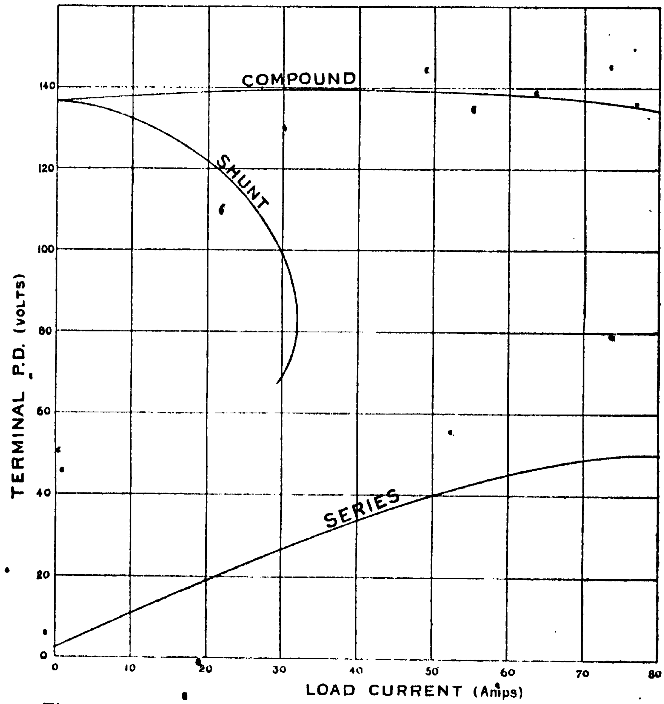


Fig. 38*b*. Load Characteristic for Compound Wound Dynamo.

gives a rising characteristic up to the point of saturation of the iron. Remembering that the characteristic of a shunt dynamo is drooping, it is obvious that by combining the two effects in suitable proportions, a machine may be obtained which will give an approximately constant voltage over a certain range of load. Such machines are known as compound wound generators,[1] and are largely used in generating stations

[1] In some cases compound wound dynamos have been built with the series turns opposing the shunt, the object being to give a drooping characteristic. This arrangement has been adopted in machines required to supply current for large arc lamps so as to reduce the current when the arc is struck.

which supply current for traction purposes, because, in this case, the load is often of a very fluctuating character. Compound wound machines are also useful in cases where a dynamo must run without attention.

The diagram in Fig. 38*b* shows the characteristic curve for a compound machine. In order to explain the action of the two windings, readings were obtained showing the P.D. for different values of load current, first with only the shunt winding, and then with only the series winding connected. By combining the two windings a practically constant P.D. is obtained over a wide range of load.

EXAMPLES

(1) Show by diagrammatic sketches the arrangement of field and armature windings in series, shunt, and compound machines. (C & G) (E).

(2) A shunt dynamo after being re-wound is run at full speed, but fails to excite its field magnets. What are the various possible causes, and how would you ascertain to which one the fault in this particular case was due? (C & G) (E).

(3) The resistance of the armature (including brush contacts) of a certain dynamo is 0.005 ohm. Plot a graph showing the relation between current and terminal P.D., assuming that there is no armature reaction. Open current P.D. = 500 volts, maximum current 1000 amps. The speed and excitation to be assumed constant.

(4) Make diagrams of connections for shunt and compound wound dynamos. How is the performance of a compound machine affected by the series turns being connected in opposition to the shunt turns?

(5) How does the current in the armature bars under the pole face of a continuous current dynamo affect the field distribution in the air gap? How does varying the position of the plane of commutation in the interpolar space with a given load affect the field excitation required for a constant voltage with constant speed? (C & G) (O).

CHAPTER IX

MOTORS

If a conductor which is free to move and carrying current, be placed in a magnetic field, so that it is at right angles to the lines of force, it will be found that there is a mechanical force tending to move it in a direction perpendicular both to the direction of the field and of the current. A modification of the rule given on p. 41 will enable us to determine the direction of motion when the directions of the other quantities are known. Using the left hand, hold the first and second finger and the thumb at right angles to each other. Let the first finger show the direction of the lines of force, the second finger the direction of the current, then the outstretched thumb will indicate the direction in which the conductor tends to move.

Experiment shows that the mechanical force is proportional to the strength of the field, the strength of the current, and the length of the conductor. Provided that the three quantities are perpendicular to each other, the force on the conductor may be calculated from the following formula:—

force (dynes) = strength of field (lines per sq. cm.) × strength of current (C.G.S. units) × length of conductor (cm.).

When the armature of a continuous current generator is caused to revolve and generate an E.M.F., no work will be done (excepting that required to overcome friction and other losses), provided that there is no current flowing through the armature conductors. But when current is taken from the dynamo, work must be done to turn it round, because the current is doing work in the external circuit, and this energy must ultimately come from the prime mover. When the current flows through the armature conductors, each conductor experiences a mechanical force tending to move it in the opposite direction, therefore making it necessary to do work in producing rotation. The force, and hence the torque produced, would be calculated from the formula given above.

Now suppose that instead of being driven and made to generate current, a current from another source is passed through an armature, the magnetic field remaining unaltered. The same forces which occur when the machine works as a dynamo now come into play, producing a torque in the same sense as before, and tending to produce motion in the opposite direction. In other words, a continuous current dynamo is reversible, and when it is supplied with electrical power and does mechanical work, it is termed a motor. The remarks in chapters iv., v., and vi. which relate to the construction of dynamos, apply with equal force to motors, and at the present stage it may be understood that, as regards construction, C.C. dynamos and motors are alike.

Just as a machine working as a dynamo is subject to a motor action in that the current flowing through the conductors tends to turn the armature in the direction opposite to that of its actual rotation, so in the armature of a motor, an E.M.F. is generated, because the conductors cut the flux. The E.M.F. tends to send a current through the circuit, in the reverse direction to that in which the current is flowing, and for this reason is spoken of as a back E.M.F.

* *Calculation of Torque.*—If E = the E.M.F. applied to the armature, and V = the back E.M.F. generated, the current will be given by

$$C = \frac{E-V}{R_a} \quad (1)$$

where R_a is the resistance of the armature.

Now suppose that a current C is supplied to a motor armature at an E.M.F. E. The electrical power supplied = E × C. The loss owing to heat produced in the armature windings will be C^2R_a. The differenee between these two quantities is the power turned into mechanical work.

$$\text{Mechanical power} = EC - C^2R_a = C\ (E - CR_a)$$
$$= C\ (V) \quad (2)$$

because $E = V + CR_a$ from (1) above

Now put in the value of V from chapter vi.

$$V = \frac{N.Z.n}{10^8}$$

taking the case of a machine with a ring or lap wound drum armature, where

N is the total number of conductors on the armature,
n „ speed in revolutions per second, and
Z „ flux entering the armature from one pole.

Equation 2 becomes

$$\text{mechanical power (P)} = \frac{NZnC}{10^8}\text{ watts}$$

If T = the torque produced in lb.-feet,

$$P = \frac{2\pi n T}{550}\text{ horse power,}$$

$$= \frac{2\pi \times 746}{550}.n.T\text{ watts}$$

thus
$$\frac{2\pi.746.n.T}{550} = \frac{NZnC}{10^8}$$

$$T = \frac{ZCN \times 550}{2\pi.746} = \frac{.117}{10^8}.ZCN\text{ lb.-feet.}$$

This gives the torque produced in a motor in terms of the flux per pole, the armature current and constants. Hence $T \propto Z.C$ which result might have been anticipated, since the force on a conductor depends upon the current flowing through it and the strength of the field in which it is placed. Moreover, the result shows that when the load on a motor is increased the current in the armature will increase also to supply the increased torque.

Necessity for Starter.—If equation (1) be written in the form

$$E = V + CR_a$$

and both sides multiplied by current, the equation becomes

$$EC = VC + C^2R_a$$

The term on the left represents the watts supplied electrically. C^2R_a is the power spent in heating the armature windings: if this be, *e.g.*, 5 per cent. of the power supplied, it follows that VC is 95 per cent. of EC. Thus, when a motor is working, the back E.M.F. is the important factor in determining the current in the armature. It is zero when the motor is not running, since the back E.M.F. is proportional to the speed. Hence, if the full voltage were supplied to an armature when stationary, the current which would flow through the conductors while the machine was getting up to speed would be many times the full load current. A numerical example will make this clearer. Consider a 500 volt motor; let full load current

be 20 amperes. If it be assumed that the C^2R loss at full load is 3 per cent. of the power supplied, then

$$C^2R_a = \frac{3}{100} \cdot 500 \times 20$$

$$R_a = \frac{3}{100} \cdot \frac{500 \times 20}{20 \times 20} = \frac{3}{4} \text{ ohm.}$$

Now if the full 500 volts were applied to the armature when stationary the current would be

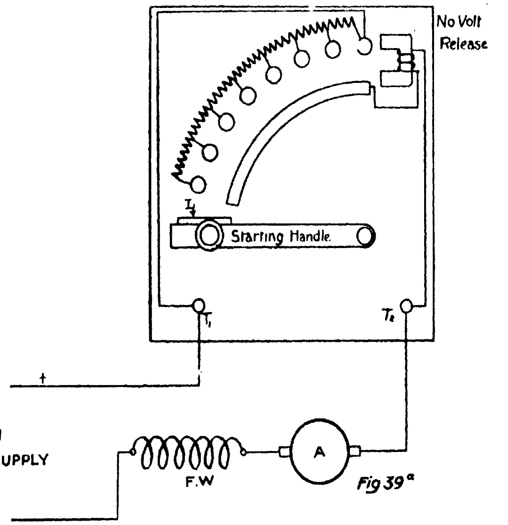
$$C = \frac{500}{\frac{3}{4}} = 666 \text{ amperes.}$$

As a matter of fact the current would not be so great as this unless the armature were prevented from turning, because before the current could have risen to the value calculated, the armature would have developed a back E.M.F. in virtue of its rotation. Nevertheless, the calculation shows that before the machine had attained full speed, a current many times as great as the full load current would pass through the armature. In addition to the possibility of damaging the armature and commutator, such a large current would cause severe fluctuations on the system to which the motor was connected and would probably blow the fuses. To avoid this rush of current when a motor is running up to normal speed, a starter is employed. In its simplest form, a motor starter is a rheostat or regulating resistance connected in series with the armature of the motor. The resistance must be such that when the switch is closed the current which will pass will not greatly exceed the full load current for the motor. As the motor speeds up, the resistance is cut out in steps, and finally the full pressure of the supply is across the motor armature.

Motor Starters.—Starters whether for shunt or series motors are usually arranged to be automatic, so that if the supply pressure be cut off, the switch arm is returned to the starting position by means of a spring, and the motor can only be restarted by cutting out the resistance in steps. In Figs. 39*a* and 39*b* are shown the connections for starters for both shunt and series motors respectively.

The starter illustrated in Fig. 40 is an example of one manufactured by Veritys Ltd. of Birmingham, and is suitable for a 10 H.P. shunt motor. Referring to Fig. 39*a* it will be seen that there is only one circuit through the starter. The current passes through from the switch arm to the resistance coils, any number of which may be in circuit according to the

position of the handle. The current also passes round the few turns on the electro-magnet. When the starting handle is moved over to the extreme right the iron plate I comes against the poles of the magnet. This serves to hold the starting handle in the running position. When the main switch is opened, or from any cause the current is interrupted, a spring pulls the handle back into the off position.

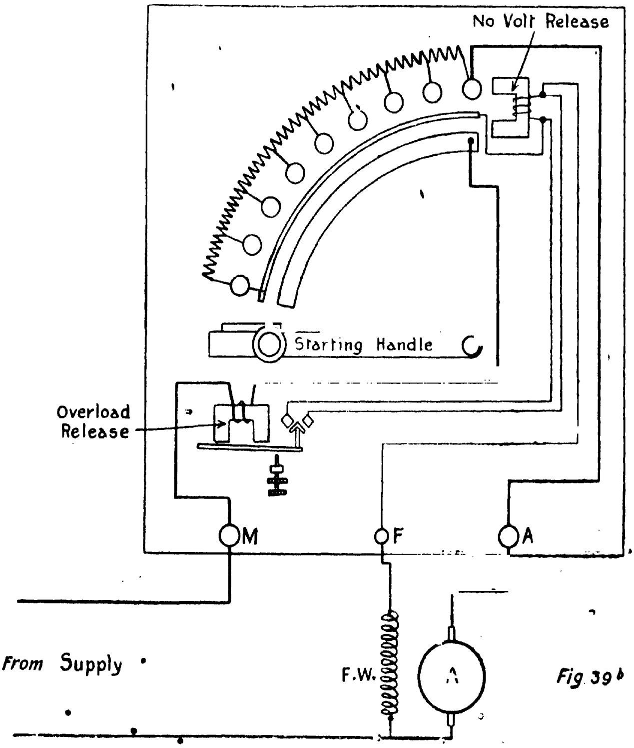


ARRANGEMENT OF STARTER FOR SERIES MOTOR.

In the case of the starter for a shunt motor, 39*b*, there are two circuits and three terminals. These are marked respectively M (main), A (armature) and F (field). The field connection is established when contact is made on to the first stud, and the current to the armature passes through all the resistance coils. The field current passing round the coils of the no-volt release magnet, holds the starting handle in the running position when all the resistance has been cut out of the armature circuit. Should the supply be cut of, or the field connection become broken, the spring pulls the handle into the off position. There is also shown in the diagram an overload release. This is an electro-magnet, the winding of which carries the full current to the machine. When the current exceeds a certain pre-arranged value, the iron armature

is attracted to the poles; the no-volt magnet is short-circuited through the contacts, and the motor is automatically stopped.

Speed Variations in Motors.—The speed of a C.C. motor will depend upon the E.M.F. applied to the armature and the flux produced by the poles. Referring to the equation,



ARRANGEMENT OF STARTER FOR SHUNT MOTOR.

$E = V + CR$, it will be remembered that the second term on the right is small compared with V. It follows from this that if E be varied, V must vary by a nearly proportional amount. Approximately therefore, $V \propto E$. But $V \propto \text{speed} \times \text{flux}$ in armature, and if the flux be constant speed $\propto E$.

This suggests one method of varying the speed of a motor.

If a rheostat capable of carrying the full load current is connected in series with the armature, the voltage across the brushes may be altered by varying the amount of resistance in this rheostat. This method is sometimes called rheostatic control. It has two serious disadvantages; firstly, it is wasteful, because if it is desired to reduce the speed of the motor to one half, the pressure drop in the rheostat must be practically equal to the voltage across the armature, which means that half the power supplied from the mains is being spent in heating the rheostat. Secondly, the "drop" produced in the rheostat will not be constant, but will depend upon the load on the machine, since the drop varies with the current. Thus, while a certain value

Fig. 40. General View of Starter for 10 H.P. Shunt Motor.

of resistance will reduce the speed by, *e.g.*, 10 per cent. at one load, the drop in speed will be greater at a higher load, because the larger current will result in a smaller voltage across the brushes.

Another method of producing speed variation in a motor is to vary the flux in the armature by means of a rheostat in the field circuit, the voltage across the brushes remaining constant. Starting with a motor running at normal speed with normal field, a reduction in field current will produce an increase in speed, but the increase in speed is not proportional to the decrease in field current. Fig. 41 shows the variation of speed with excitation produced in a motor at constant load. The explanation of this effect is as follows: when the applied voltage is maintained constant, the back E.M.F. V, developed by the machine will be nearly constant. Since $V \propto Z \times$ speed, it follows that a decrease in Z will produce a corresponding increase in speed. Although the flux Z is not directly pro-

portional to the exciting current, changes in the latter produce corresponding changes in Z, and this explains the shape of the graph. This method of producing speed variation is more efficient and more easily carried out than the rheostatic method. With machines provided with interpoles, speed variations of 1 to 4 may be obtained at full load without sparking.

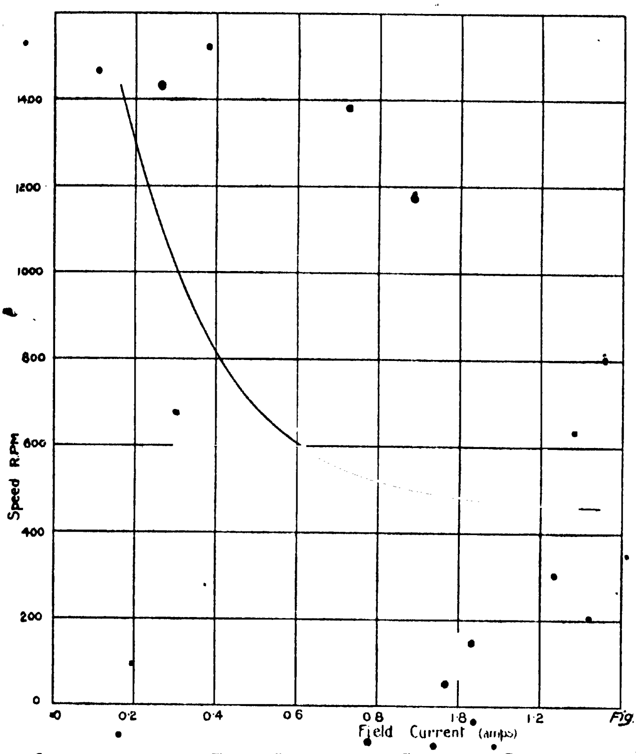
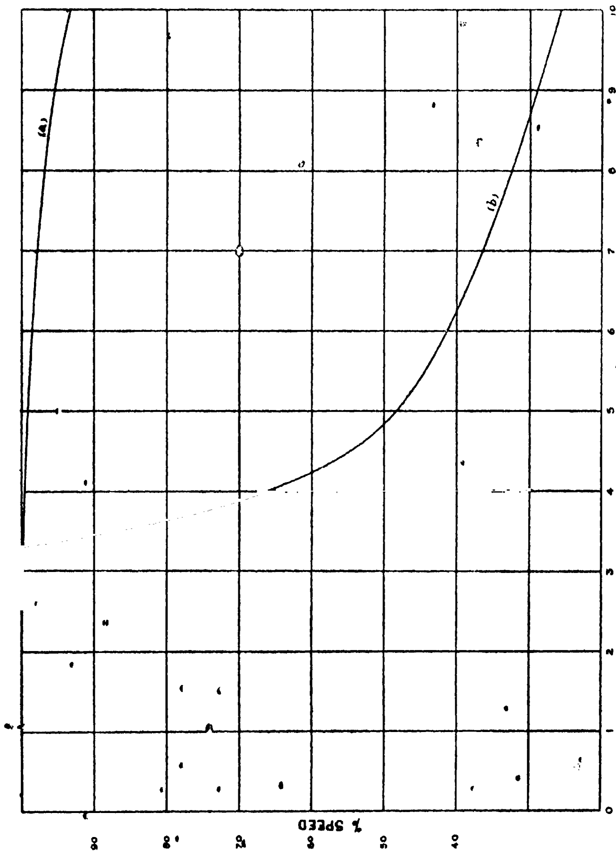


Fig. 41

RELATION BETWEEN FIELD CURRENT AND SPEED FOR SHUNT MOTOR, LOAD CONSTANT.

Characteristic Curves for Motors.—The speed at which a C.C. motor will run is dependent upon several factors, and a graph showing the relation between speed and load may be called the load characteristic. Fig. 42 shows the shape of the characteristic curves for shunt and series machines. Considering first of all the shunt machine, it should be noted, that apart from the change in exciting current produced by change in

temperature of the field winding, the field current will be constant and independent of the load, so long as the supply pressure remains unaltered. Hence, apart from armature



Relation between speed & Output of (a) Shunt Motor with interpoles (b) Series Motor. Fig. 42

reaction, the field in the armature may be regarded as constant. Now if we consider the fundamental equation of a motor

$$E = V + CR$$

it will be seen that since E is supposed constant the sum of the two terms on the right will be constant. Moreover, CR

will increase proportionally with the load on the machine; hence, as the load increases, V will decrease. But V, the back E.M.F. is directly proportional to the product of speed and flux. Consequently, an increase in load will cause V, and hence the speed, to be reduced. Notice that the larger the armature resistance, R, the more rapidly will the speed drop as load increases.

It is now necessary to consider the effect of armature reaction on the speed, and as we have dealt with a two-pole machine in the case of dynamos, we shall select a multipolar machine. In Fig. 43 is shown a portion of the armature of a motor. For simplicity, the conductors are shown mounted upon the surface of the core. Using the left hand rule, the direction of the current is clearly as shown, with the brushes in the fixed neutral position, Fig. (*a*). Considering the north

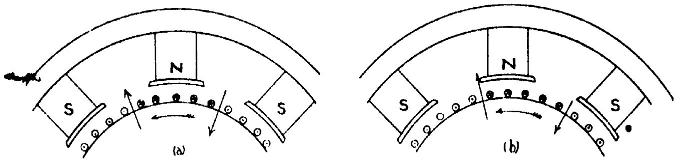


Fig. 43.

To explain Armature Reaction in Motors.

pole, the effect of the currents in the armature is to strengthen the field under the leading tip, and to weaken the field under the trailing tip, so that on the whole, the back E.M.F., and hence the speed, will remain nearly constant. But if the brushes be given a backward lead (*b*), which might be adopted in order to obtain sparkless running, the axis of magnetisation of the armature by the currents is also moved backwards, and while the magnetism in the leading tip of the north pole continues to be strengthened, that in the trailing tip is very much weakened. Thus on the whole, the conductors move in a weaker field, and the machine will have to run faster in order to generate the same back E.M.F. The effect of the armature reaction in a motor is to tend to keep the speed up as the load increases, and setting the brushes with a backward lead will give a more nearly horizontal characteristic than would be obtained with the brushes set in the fixed neutral. This explains why the shunt motor gives such a useful characteristic, and is particularly suitable for most industrial purposes where a drive at constant speed is required.

Series Motors.—With series wound motors, the magnetising current being identical with the armature current, will vary

with the load on the machine. At heavy loads, the current required to turn the machine round is large, and in this case there is a strong field and large armature current at the same time. When the motor is exerting a large torque, the speed will be low, and when the motor is lightly loaded the speed will be very high. Fig. 43 (*b*) shows the variation with speed for different loads in the case of a series motor.

Uses of Shunt and Series Motors.—If the load were entirely removed from a series motor, the speed would rise to a dangerous value, and in cases where such machines are used for driving, they are usually arranged so that the load cannot all be taken off. For example, a belt drive would be unsuitable with any but a very small series motor. The valuable property of series motors is that when they are exerting a large torque, the speed is low. This quality makes them suitable for traction purposes; that is, driving electric cars and electric trains. For the same reasons, series motors are preferred for working cranes, hoists, capstans, etc. Cases occasionally arise where a large starting torque is required, and yet the motor must not run up to a dangerous speed when all load is removed. For such work, a compound wound machine with shunt and series turns acting in the same way may be adopted.

For driving machines at constant speed, shunt motors are the most suitable because, as explained above, the speed does not vary greatly with changes in load. Shunt motors are not suitable for driving machines where the power taken is rapidly fluctuating, because they do not immediately respond to changes in load and considerable variations in speed may result. A good example of this is the individual driving of looms, and for this purpose shunt wound C.C. motors are unsuitable.

EXAMPLES

(1) It is desired to run a shunt motor at varying speeds when supplied with current from constant pressure mains. What are the advantages, disadvantages, and limitations, if any, of adopting one or other of the following arrangements: (*a*) Varying the speed by means of a rheostat in series with the armature, (*b*) by means of a rheostat in the shunt circuit?

(2) Sketch and describe a starter, equipped with no voltage and overload releases, suitable for use with a 10-H.P. 220-volt motor. About what resistance should such a starter have?

(3) Is the direction of rotation of a motor changed when the polarity of the supply mains, to which it is connected, is reversed in the case of (*a*) a shunt motor, (*b*) a series motor? If not, why not?

(4) In connecting up a 10-H.P. shunt motor, the connections to the "main and "armature" terminals on the starter have been accidentally interchanged. Describe the effect of this on the starting properties of the motor (unloaded) and on the ultimate speed attained.

(5). Make a diagram, showing how a shunt motor is connected to the supply mains. How would you measure the power required to drive such a motor?

(6) What are the essential differences between a series motor and a shunt motor? What type would you use for driving an electric fan? Give reasons for your answer. (C & G) (E).

(7) Imagine you have a large powerful electro-magnet, such as might belong to a dynamo machine, and with only a short gap between the poles, also that the magnet is excited so as to produce a very powerful field in the gap. Say what you know about the effect which would be produced on a conductor passing freely through the gap, when a current of 100 amperes was caused to flow through the conductor. (C & G) (E).

(8) A vertical conductor is passed in front of the north pole of a magnet from right to left. What is the direction of the induced E.M.F.? Supposing this conductor to be carrying a current in an upward direction when in front of the pole, which way will it tend to move?

(9) A conductor carrying a current of 500 amperes is placed in a magnetic field, the flux density of which is 10,000 lines per square centimetre. Calculate (*a*) the force in dynes on each centimetre length, and (*b*) the force in lbs. on each foot length.

(10) An electric car running at 12 miles per hour takes 50 amperes at a pressure of 540 volts. If energy is charged at the rate of 2d. per B.O.T. unit, calculate the cost of running the car a mile.

(11) Make a diagram of connections for a starter for a shunt motor, showing no volt and overload releases.

(12) Show by a sketch the relation between the direction of rotation of armature, current in armature conductors, and magnetic flux in a C.C. motor. What is meant by the term "back" or "counter" electro-motive force? (C & G) (O).

(13) Suppose you wind additional turns on the field coils of a shunt motor using the same size of wire, what will be the effect on (*a*) the efficiency, (*b*) the speed? (C & G) (E).

CHAPTER X

COLLECTION OF CURRENT—LOSSES—EFFICIENCY

Commutation.—It has been shown in chapter vi. that the alternating E.M.F. developed in the windings of a C.C. armature, may be made to give a practically constant P.D. between the brushes through the action of a commutator. The mechanical details of the commutator were described on p. 65. It remains to examine in detail the precise action which takes place at the collection of current by means of the brushes. In Fig. 44 is shown a number of segments of a machine, and the armature winding is represented by the coils

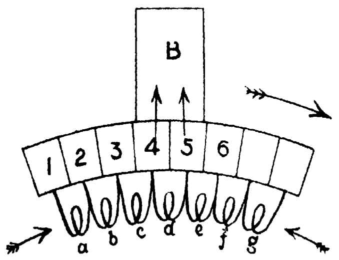
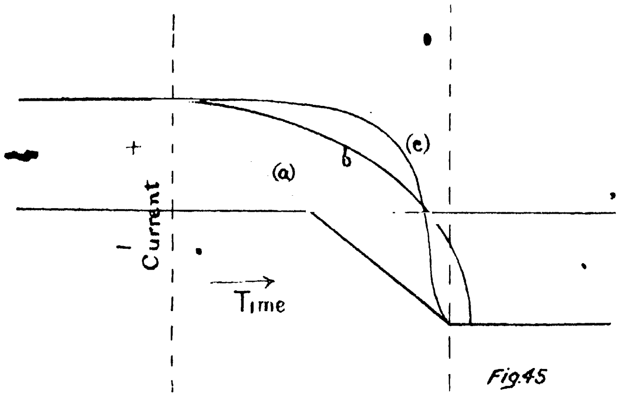


Fig. 44.

To explain Commutation.

a, *b*, *c*, etc., connected between adjacent segments. The student may for simplicity think of a ring winding, but the same consideration will apply whatever kind of winding is adopted. The brush is represented by B, and, as will be seen, is sufficiently wide to completely cover two segments. Now the current in any coil on the armature will have to reverse in direction, when the segments of the commutator to which the coil is connected pass under a brush, because a coil in the position of *a* will have the current flowing from left to right, and in a coil such as *g* the current flows in the opposite

direction. The current in both cases is half that collected by the brush. For example, suppose that the current collected by B is 100 amperes, the current in coil *a* will be 50 amperes and also that in *g*. As long as the segment 2, to which coil *b* is connected, is not making contact with the brush, the current in *b* will remain constant. But when 2 touches B, some current will immediately begin to pass from 2 to B, and hence the current in *b* will diminish. It may be assumed for the moment, that the amount of current passing from a segment to a brush is determined by the area of contact between the brush and the segment in question, the current entering the brush being distributed between the segments in



GRAPHS SHOWING VARIATION OF CURRENT DURING COMMUTATION.

direct proportion to the area of contact. In the present case, when 2 and 3 make equal contact with B, the current in the coil *b* will have fallen to zero. Further, with the assumption mentioned above, no current will be flowing in a coil when it is in the neutral position. The change in current may be conveniently represented by a diagram, such as that shown in Fig. 45. The time which elapses from the instant when the current in a coil begins to diminish, to the instant when it has arrived at full strength in the reverse direction, is known as the interval of commutation. Curve (*a*), Fig. 45, represents the change in current in a coil on the assumption given above. When the current changes in this way, the commutation may be called ideal, but it is never attained in actual machines.

The assumption made here, that the current passing from

a segment of the commutator to a brush is determined solely by the area of contact between that segment and the brush, is not justified for the following reason. It must be remembered that each of the coils of the armature winding consists of one or more turns of wire which are very largely surrounded by iron. Hence, when a current is passing through a coil, a large number of magnetic lines will be linked with it. In consequence, when the current through a coil is changing, there will be an E.M.F. set up, which will tend to prolong or retard the current, according to whether the current is increasing or decreasing. The more turns there are on each section of the winding, and the greater the rate of change of current, the larger will this E.M.F. be. This E.M.F. interferes with the change of the current, and the latter will vary in a manner represented by some such curve as (*b*), Fig. 45. It will be seen from this graph that at the middle of the interval of commutation the current in a coil has not fallen to zero, and at the end of the interval—*i.e.*, at the moment when the segment to which a coil on the armature is connected has parted from the brush—the current has not risen to its final value in the coil in question, and must continue for a short interval to pass from the trailing segment to the brush. Just at the instant when the brush and the segment part, the current density in both will be very high where they touch, hence there is great local heating. This, in conjunction with the high E.M.F., caused by a very rapid change of current through the armature coil, will give rise to sparking and arcing.

There are two methods by which sparking may be prevented. The first, known as "resistance commutation," involves the employment of brushes which give a high contact resistance between the brush and the commutator, and therefore a large drop of potential there. This condition is fulfilled by carbon brushes, and for this reason the brushes of most modern machines are blocks of carbon. The second method is called E.M.F. commutation. In order to reverse the current in a coil all that is necessary is to provide an E.M.F. which will oppose the induced E.M.F. caused by the change in current. A glance at Fig. 44 will show that this E.M.F. must have the same direction as that in coils to the right of the neutral axis. Therefore, if the next pole is moved backwards, or, what comes to the same thing, the brushes are moved forward, or a flux is provided in the same direction as that given by this pole by some other device, the coils undergoing commutation, instead of being in a neutral position, will have an E.M.F. produced in them which will help to bring about the desired reversal. Curve (*c*), Fig. 45, shows

the manner in which commutation takes place in an actual machine. We saw in chapter viii. that in order to keep the brushes in the neutral position, they have to be advanced in a dynamo as the load increases, unless the armature reaction is neutralised by commutation poles; this is called "giving a lead." With machines provided with interpoles, the brushes may be kept in a fixed position, otherwise they have to be placed in advance of the neutral axis by an amount which increases with the load.

In the case of motors, for a given direction of current and field distribution, the rotation is opposite to that of a dynamo. Therefore, instead of moving the brushes forward they have to be moved in the opposite direction to that in which the machine is running. This is known as "backward lead."

It was formerly the custom to employ copper gauze brushes, particularly for dynamos, and to adjust their position according to the load, till the sparking disappeared or was reduced to a minimum. This method is now rarely employed, and nearly all machines are provided with carbon brushes, and many machines with commutating poles. In machines not so provided, the brushes are given a slight forward lead in the case of a dynamo, or a backward lead for a motor, the positions for each direction of running being marked on the machine by the maker.

The high contact drop produced with carbon brushes has the disadvantage that it reduces the terminal P.D. of the machine. The drop varies slightly with load and also with the grade of carbon and the mechanical pressure, but is usually from 1 to 1½ volts per brush. An average value of 1¼ may be taken, which means that 2½ volts is lost on account of two contacts in series. This means 2½ per cent. loss in a 100-volt machine, but only ½ per cent. in a 500-volt one, in which case the advantage gained quite outweighs the loss. With carbon brushes the commutator is much less worn.

Losses in Machines.—The losses which occur in dynamos and motors may be studied by means of the following table:—

Losses in dynamos and motors

- Mechanical losses
  - Bearing friction
  - Brush friction
  - Windage
- Electrical losses
  - Copper
    - Armature
    - Field windings
    - Commutator and brushes
  - Iron
    - Hysteresis
    - Eddy currents

Mechanical Losses.—These form, as a rule, not a large percentage of the total losses, usually ½ to 3 per cent., the former figure for very large machines. The loss due to the setting of air in motion must be regarded as useful, as it is a valuable cooling agent.

Electrical Losses.—Losses which occur in the iron armature core, and to a small extent in the pole shoes, are known as iron losses. They are produced in two distinct ways. Eddy currents are set up in the armature core, and to reduce these the core is laminated, chapter vii. The loss produced by eddy currents depends on the extent to which this subdivision of the core is carried out—*i.e.*, on the thickness of the plates, the speed, and the flux density in the core. In order to keep down the eddy currents, the cores should be carefully built up. The modern method of pasting paper on the iron sheets before punching does not result in such good insulation as the more laborious method of building up the core with interleaved paper, on account of the inevitable burrs left by the punching machine.

Hysteresis Loss.—In order to alter continually the direction of magnetisation of iron, a certain amount of power must be supplied, which, of course, is all turned into heat in the core. In general, the softer the iron, the less will be the amount of this loss. There are two kinds of hysteresis loss, according to the way in which the magnetisation is changed. Firstly, when the axis of magnetisation is constant, and the amount of flux is continually changing, being introduced first in one direction and then in the other, we have what is described as alternating hysteresis. This is the action which occurs in alternating current transformers and choking coils, and principally in the teeth of armature cores. Secondly, when the amount of flux is constant, and the direction of magnetisation is constantly changing, we have rotational hysteresis set up. In the armature of a C.C. dynamo, both kinds of hysteresis are produced—rotational hysteresis chiefly in the core below the slots, and alternating hysteresis chiefly in the teeth, although there is the other effect present at the same time.

Now the two kinds of hysteresis loss do not follow the same law, and as it is difficult to separate the effects, not very much is known about them. It is generally assumed, that while the alternating hysteresis increases indefinitely with the flux density, the rotational effect reaches a maximum, and at very high flux densities is reduced to zero. The student should notice that, unlike the eddy current loss, the hysteresis loss is due to an inherent property of the material, and cannot be reduced by any such process as lamination. It can only be kept down by keeping the flux density low and choosing good specimens of

iron. There are some alloys now sold for armature cores which give lower hysteresis losses than pure iron. "Lohys" is one of these.

Copper Losses.—The copper losses or C^2R losses, in a machine are quite definite, and may be calculated, provided the resistance of, and current in each part are known. The effect of C^2R losses in the armature windings, added to the iron loss, is to cause the temperature of the armature to rise. Quite apart from loss of power, the disadvantages of having the armature hot are that the resistance of the windings is increased, and the insulating materials tend to deteriorate more rapidly at high temperatures, particularly when, as in the case of a revolving armature, they are also subject to mechanical stresses. Notice that in calculating the C^2R loss, the resistance must be determined at the high temperature.

The C^2R losses in the field windings may be calculated in the same way. The resistance of a series winding may be included with the armature resistance for purposes of calculation. There are small losses in the commutator produced by eddy currents, and there are, of course, C^2R losses in the brushes and connections. A most important source of loss is the contact resistance between brushes and commutator in the case when carbon brushes are used.

As explained on page 91, the drop at the brushes may be taken as $2\frac{1}{2}$ volts, and the loss in watts is found by multiplying this by the current. Another loss is produced by the local currents which flow round an armature coil and through a brush, when the segments are short circuited by the brush.

Constant and Variable Losses.—A little consideration will show, that of the losses mentioned above, some are constant or practically so, and others will vary with the load on the machine.

With all except variable speed motors, the mechanical losses and the iron losses are practically constant, although, as a rule, the effect of armature reaction is to increase hysteresis and eddy current losses. The excitation loss in the case of a shunt winding will be constant as long as the field current is not varied. On the other hand, the C^2R loss in armature and series windings will increase as the load on the machine is increased. These losses increase as the square of the load current: for example, they are four times as large at full load as at half load, and indeed rather more than four times, because at the full load the resistance of the windings will be higher.

Efficiency. — Of the total power supplied to a machine,

mechanically in the case of a dynamo, electrically in the case of a motor, a certain amount is wasted in supplying the losses, and the remainder is given out in another form of energy. The power supplied is termed the *input*, and the power given out, the *output*. The ratio of output to input is known as the *efficiency*, and may be denoted by the symbol *e*.

Thus $$e = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}$$

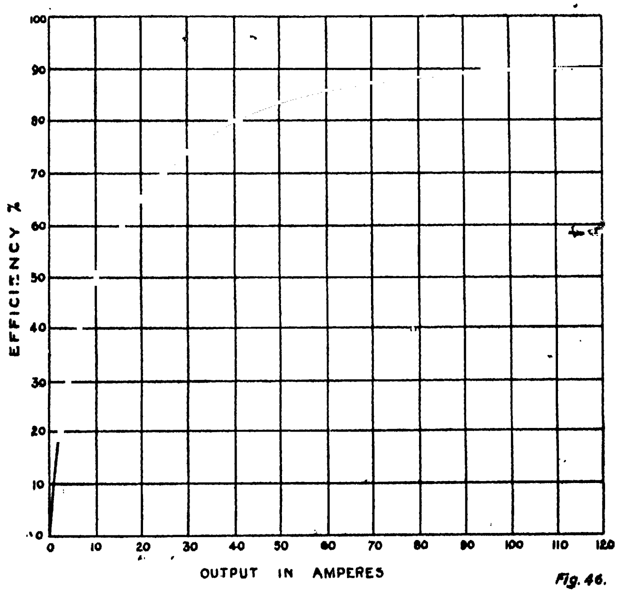


Fig. 46.

EFFICIENCY OF 550 VOLT, 100 AMPERE GENERATOR AT VARIOUS LOADS.

When the output and the losses are known, or the input and the losses, the efficiency may be calculated. Since the output at no load is zero, the efficiency of any machine must be zero when unloaded. In Fig. 46 is shown a typical curve, giving the efficiency at various loads for a medium-sized generator.

Some of the losses are proportionally larger in small machines; therefore large machines have, as a rule, a higher efficiency than small ones.

The manufacture of dynamos and motors has become so

standardised that the efficiencies of machines by different makers do not vary greatly. Fig. 47 shows the full load

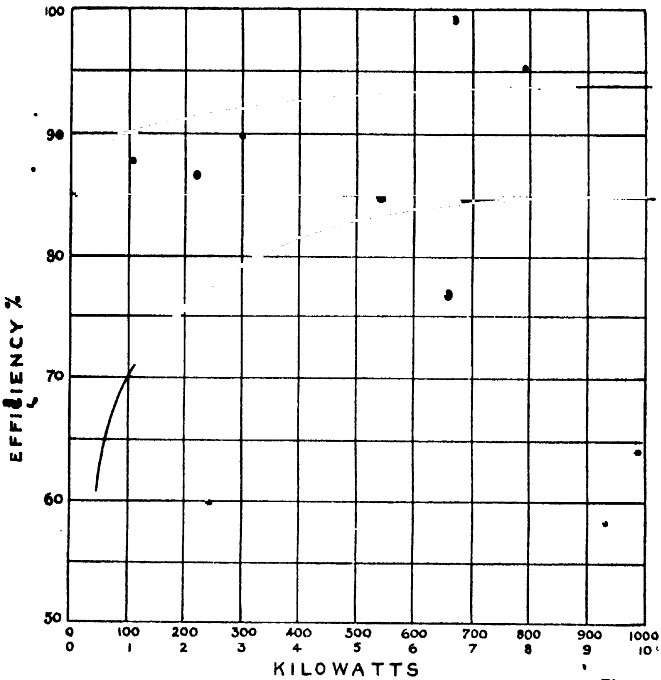


Fig. 47

Average Values of Full Load Efficiency for Generators of Different Outputs.

efficiency for various sizes of machines, the values being an average of different makes.

EXAMPLES

(1) A current of 1000 amperes is collected from a machine having 12 brush spindles. If the contact area of each brush is 1 square inch, how many brushes may be employed per spindle, allowing 50 amperes per square inch?

(2) A 40-H.P. 400-volt shunt motor takes 5 amperes to drive it at no-load. Find the efficiency of the machine at half-load and full load, assuming resistance of field winding to be 200 ohms and that of the armature circuit (between brush leads) to be 0.018 ohm.

(3) Explain the action of the commutator of a C.C. dynamo. (C & G) (E).

(4) Explain what is meant by the terms "series dynamo," "shunt dynamo," and "compound dynamo." Give diagrammatic sketches of the circuits of 4-pole machines of each of these kinds. State approximately what you would expect the resistances of each of the different parts of the circuits to be for machines of 50 kilowatts to work at 220 volts. (C & G) (E).

(5) Name the several causes of waste of energy in a C.C. dynamo and state what devices are necessary, and what precautions should be taken to insure these being a minimum in any particular design. (C & G) (O).

(6) Discuss the merits and demerits of "resistance" commutation and "E.M.F." commutation in D.C. dynamos, and point out the conditions under which one or other is to be preferred. (C & G) (O).

(7) What is meant by the terms "hysteresis loss" and "eddy current loss" in the iron cores of dynamo armatures? Why are these cores laminated, and how are the losses affected by the thickness of the plates? (C & G) (O).

CHAPTER XI

ELECTRIC HEATING

Heat and Work.—It has been explained in the earlier parts of this book, that when a current is passing through a conductor, a certain amount of electrical energy is turned into heat energy. When no mechanical work is done, the principle of the conservation of energy asserts that the amount of heat produced will be equal to the amount of electrical energy which is absorbed. It is quite correct to speak of the amount of heat produced as so many joules, or the rate of production of heat as so many watts, but it is usual to measure heat in other units. The amount of heat required to raise the temperature of a certain quantity of matter through 1° F. is not the same for all kinds of matter, and therefore a standard substance must be chosen for reference. For various reasons which cannot be discussed here, water has been chosen as this substance. The amount of heat required to raise 1 lb. of water through 1° F. from 60° to 61° F. is known as a "British Thermal Unit of heat," indicated by "B.T.U.," and this unit is used by most British engineers.

In a similar way the amount of heat required to raise 1 gram of water from 0° C to 1° C, is known as a "calorie," and this unit of heat is used by most scientists. The correspondence between the amount of heat produced and the amount of electrical energy required to produce it, leads to a definite and constant relation between the electrical units of energy and the units of heat.

Joule and others determined this relation with great accuracy, and found that 1053 joules are equivalent to 1 B.T.U.

Resistance Heating.—For producing heat electrically two methods are used. In one, a current is passed through a wire or strip of some suitable material, which is wound on mica or embedded in enamel, and mounted as closely as possible to the place where the heat is required. Most domestic heating appliances, such as electric kettles and radiators, work on this

principle. In Fig. 48 is illustrated an electric iron made by the Electric Ordnance and Accessories Co. of Aston. The heating element consists of several yards of wire made of an alloy of nickel and chromium, wound on two strips of mica. The size of the heater may be seen by referring to Fig. 48*a*. This particular iron takes a current of 1.4 amperes when run from a 200 volt circuit, the power required being therefore, 280 watts. The heater is covered above and below with mica, and is clamped between the sole of the iron and the top plate by two nuts, which also hold the handle in position.

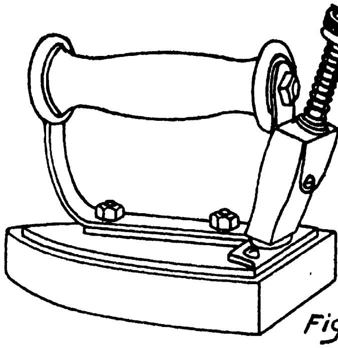


Fig 48

GENERAL VIEW OF ELECTRIC IRON.

The Electric Arc.—When a very high temperature is required an electric arc is employed.

It is well known that when a circuit through which a current is passing is broken, a spark is produced where the break takes place. Under certain conditions the spark may be made continuous, and it is termed an "arc." One of the essential conditions is, that the E.M.F. of the circuit shall exceed a certain minimum value which depends upon the substances between which the arcing takes place.

The points, or ends of the circuit, between which an arc is maintained, are called the electrodes. The minimum E.M.F. for electrodes of copper is about 12 volts, and for carbon electrodes about 35 volts. The first person to produce and study an arc was Sir Humphrey Davy, who formed arcs with the large primary battery at the Royal Institution. Because the spark bends upwards, when the electrodes are horizontal, owing to convection currents in the air, Davy named it an *arc*. The name is now employed for a spark which persists

for even a short time, whether it is curved or not. In nearly all cases where an arc is employed in engineering, electrodes of carbon are used. They take the form of pencils which are generally round, and are made from gas carbon.

In order to study the appearance of an arc, it is necessary to see an image of one projected on a screen; no photograph or drawing gives an adequate representation. If an arc which is supplied with continuous current be examined in this way, it will be noticed that the end of one of the electrodes, the positive,[1] is much brighter than that of the other. The hollow

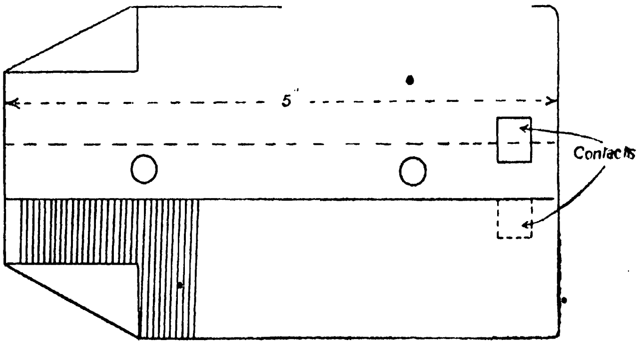


FIG. 48a. HEATER FOR ELECTRIC IRON.

which is formed at the end of the + carbon is the region of the highest temperature, viz., about 3500° C. The temperature of the negative carbon is about 2500° C.

When studying the appearance of an arc on a screen, it will be noticed that the length of the arc is constantly increasing. This is due to the burning of the carbons at the ends. Unless the carbons are fed forward, a point will ultimately be reached when the arc will be longer than can be maintained with the circuit voltage, and it will go out. To start the arc again, the carbons must be put into contact and then separated; this is called "striking the arc."

The appearance of an arc supplied with alternating current is somewhat different. Since first one electrode and then the other is positive, the ends of both carbons are similar; moreover the temperature of the carbon ends is not so high as that of the positive crater of a C.C. arc.

[1] The electrode where the current enters the arc.

An important accessory in connection with an arc is the steadying resistance. The object of this is threefold.

(1) It renders the arc electrically stable.

(2) It prevents a large current flowing when the arc is being struck.

(3) In the case of automatic lamps, the regulation may be partly or entirely effected by a shunt solenoid.

It will be readily understood that an arc is an exceedingly useful and convenient means of producing high temperatures. In various commercial processes, arcs are used for this purpose: When an arc is produced inside a firebrick chamber, the arrangement is called an electric furnace, and several metallurgical processes, such as the refining of steel, are carried out by its aid.

Calculation of the Cost of Electric Heating.—The relation between the joule and the calorie will enable the cost of producing heat electrically to be calculated.

Since 1 calorie = 4.18 joules and
1 kilowatt hour = $1000 \times 60 \times 60 = 3{,}600{,}000$ joules, it follows that $\frac{3{,}600{,}000}{4.18}$ or 860,000 calories of heat will be produced (assuming no loss) by the expenditure of 1 B.O.T. unit. Thus for a certain price per unit the cost of producing a definite quantity of heat is easily determined.

The efficiency of electrical heating apparatus is limited only by the fact that some of the heat will go to raise the temperature of other bodies besides the one it is desired to warm. Thus the heating element of an electric kettle will raise the temperature of the kettle itself, the kettle stand, the air, etc., as well as that of the water in the kettle.

Example.—Calculate the cost of boiling 1 quart of water in an electric kettle of 80 per cent. efficiency, initial temperature 10° C. What will be the time taken if the pressure is 220 volts and the current 2 amperes? Cost of energy 2d. per B.O.T. unit.

Power taken from supply $= 2 \times 220 = 440$ watts.

power spent in heating water $= \frac{80}{100} \times 440 = 352$ watts.

1 quart of water weighs $2\frac{1}{2}$ lbs. = 1140 grams about.

To raise this quantity of water from 10° C. to 100° C requires $1140 \times 90 = 103{,}000$ calories, equivalent to 430,000 joules.

Therefore time $= \frac{430{,}000 \text{ joules}}{352 \text{ watts}} = 1220$ seconds or $20\frac{1}{2}$ minutes,

energy supplied $= 352 \times 20.5$ watt-minutes $= 0.12$ kilowatt hours, and cost $= .12 \times 2\text{d.} = \frac{1}{4}\text{d.}$ about.

The advantages of electric heating for domestic purposes from the point of view of cleanliness and convenience, are too obvious to need insisting on. The difficulty in most cases lies in the high cost. Calculations like that given above seem to show that the cost is a trifling matter, but a few moments consideration show that it would be heavy if all the operations in a house were carried out by electrical methods. For instance, it is easy to show that the cost of boiling an egg or of heating a room for an hour is small, but in an average household, about 50 gallons of hot water are used per day, and this is heated as a rule by the same fire which warms the kitchen and which often does the cooking. To heat 50 gallons of water electrically from 10° C to 60° C will cost 1s. with current at 1d. per unit. Another difficulty is the large current required and the cost of the wiring and fittings, to say nothing of the heating apparatus. Until the cost of energy supplied by local authorities is very much reduced, the prospects of an extended application of electrical methods of heating in all but wealthy households are remote.

EXAMPLES

(1) An electric kettle has an efficiency of 95 per cent. With current at 3d. per B.O.T. unit, how much will it cost to raise 2 pints of water from 15° C. to 100° C.? Find the time required for this operation with a current of 2 amperes at 220 volts. (C & G) (O).

(2) An electric radiator, connected to a 220 volt supply is found to take a current of 7 amperes. Calculate the number of calories produced per second and the cost of running per hour with energy at $1\frac{1}{2}$d. per B.O.T.

CHAPTER XII

ELECTRIC LAMPS

ELECTRIC lamps fall naturally into two classes: (1) Filament or glow lamps, often called incandescent lamps; (2) Arc lamps and vapour lamps.

Filament Lamps.—Filament lamps are those in which a thread or filament, usually of circular cross-section, is heated to incandescence by the passage of a current.

A body which is heated to a temperature above its surroundings, dissipates the energy which is supplied to it in three ways. These are respectively named, conduction, convection, and radiation. As a rule all three processes occur simultaneously, but by placing a body in a good vacuum, the losses due to convection and conduction are reduced to a very small amount. Some heat must always be carried away by the leading in wires in an electric lamp, but this, too, is small.

Radiation is the name given to that process of transmitting energy which does not involve the presence of material substances. For example, the heat and light which come to us from the sun through the interstellar space, are transmitted in the form of radiant energy. For the purpose of explaining the effects produced, all space is supposed to be filled with an imponderable substance which is called the ether, and the transmission is said to be effected by vibrations or waves in the ether.

When a body is heated to a temperature of, say, 300° C, its appearance will not differ from its appearance when cold. But if the temperature be raised to 600° C, the body will begin to be luminous and give out red light. In homely language, the body is red hot. Further heating results in a bright red, a yellow, and finally a white heat. Now although a body which is white hot is radiating energy by the same process as a body which is not even a dull red, there is this difference between them. The radiation in the one case is luminous, that is, it affects the nerves of the eye; in the other, it is non-

luminous. Students of physics will understand that the difference lies in the wave length or the frequency of vibration of which the radiation is composed. It will have to be assumed here that a body at a low temperature emits waves up to a certain frequency but not beyond. Increasing the temperature increases the maximum frequency present in the radiation. Now the radiation which we call red light, is of lower frequency than that of yellow, and yellow again is lower than blue. As we pass along the spectrum from red to violet, there is a continuous increase of frequency. The radiation which is of lower frequency than red light is non-luminous, and so is radiation of a higher frequency than violet. Just as we cannot distinguish by the ear notes either above or below a certain frequency, so our eyes are only tuned to make use of radiation between certain limits. It is interesting to notice that whereas radiation of a lower frequency than red light, known as infra red, is not harmful, the radiation of a higher frequency than violet is exceedingly injurious to the eyes, and should be very carefully guarded against.

From what has been said, it will be understood that when light is produced by heating a body, a certain temperature must be attained in order that the light should be of the desired colour. Nor is this all. It has been found that the higher the temperature to which a body is raised (at any rate up to 5000° C), the larger is the proportion of radiation falling between the limits of vision. In other words, the higher the temperature of a luminous body, the greater will be the proportion of luminous to non-luminous radiation obtained from it. The ratio $\frac{\text{luminous radiation}}{\text{non-luminous}}$ may be called the efficiency of a source of light. Thus to produce a highly efficient lamp it is necessary to raise the light giving substance to a high temperature.

A substance, in order that it shall be suitable for an incandescent lamp filament, must possess the following properties:—

(1) It must conduct, at any rate, at high temperatures.
(2) It must be capable of standing a high temperature without change for a long time.
(3) It should preferably have a positive temperature coefficient.
(4) It should be capable of being drawn into wire and should be inexpensive.

It may be stated at once that no substance is known which possesses all these properties. In the following table will be

found the most important substances, both metallic and otherwise, which have high melting points.

LIST OF SUBSTANCES HAVING HIGH MELTING POINTS.

Substance.	Approximate Melting Point.	Experimenter.	Remarks.
CARBON	...	Swan, Edison, etc.	Volatilises without fusing.
Iridium	above 2000° C.	Gülcher	Practical lamps produced, but not sold.
Molybdenum	about 1800° C.	...	...
Niobium	...	Siemens	...
OSMIUM	above 2500° C.	Welsbach	Metal 5/- per gram.
PLATINUM	1750°–1800° C.	Edison and others	M.P. too low.
Rhodium	above 1800° C.	...	...
Ruthenium	above 2300° C.	...	Next to osmium, most infusible substance known
Silicon	...	...	...
TANTALUM	2250°–2300° C.	Siemens	Capable of being drawn.
Thorium	...	O. Nernst M. Siemens	...
Titanium	...	...	...
TUNGSTEN	3000° C.	Kuzel Auer Gas Co., Vienna Just-Hanaman G. E. Co., America Siemens and Halske	Lamps originally produced by squirting, now by drawing.
Uranium	...	...	...
Vanadium	above 1800° C.	Swinburne B. von Bolton	M. P. too low.
Yttrium	...	Siemens Nernst C. Sander	...
Zirconium	...	M. Siemens	...

Note.—If substance is printed in *italics*, filaments have been produced. If substance is printed in SMALL CAPITALS, practical lamps have been sold.

Many of these substances are little more than chemical curiosities and very little is known of several of them. We shall now consider, in historical order, the various lamps which have been introduced which can be considered in any way of practical interest.

Platinum.—Lamps with platinum filaments were first made

about 1850, but were not turned out in any great numbers. Platinum, although easily made into a filament, crystallises under the influence of high temperature.

Carbon.—Lamps with carbon filaments are too well known to need description. The early work was done by Sir Joseph Swan, Edison, and others.[1] Various processes have been brought out for producing carbon filaments, but the squirting process described below is the only one in general use.

Cotton wool is dissolved in chloride of zinc to form a syrup which is afterwards squirted through dies into alcohol. The zinc chloride is dissolved out and the thread hardens. It is then cut into the desired lengths and afterwards carbonised. This is accomplished by heating in a furnace out of contact with air. The filament is mounted on to platinum leading-in wires, which are afterwards sealed into the glass bulb. A good joint between the platinum and the carbon is made in the following way. The filament is immersed in some liquid hydro-carbon, and a current is passed through, a bridge piece being provided so that the current does not pass all round the filament, but only through the joint. This causes carbon to be deposited at the joint, and a good contact is assured. The filament is then flashed. This process consists in depositing a thin layer of carbon over the whole of the filament, by heating it in an atmosphere of hydro-carbon vapour. The deposited carbon obtained by flashing is found to be more durable than the squirted core. After the filament is mounted in the bulb, the lamp is exhausted, capped, and finally tested.

Despite the competition of the more efficient metal lamp, great numbers of carbon lamps are still manufactured on account of the low cost.

Efficiency. — In speaking of lamps, the term efficiency is not used in the scientific sense defined above. In order to produce a certain amount of light, the electrical power which must be supplied, will depend upon the temperature to which the filament is raised; the higher the temperature the less will be the power required, and *vice versâ*. The amount of light emitted is generally measured in candle power, and the power supplied expressed in watts. Hence the number of C.P. produced per watt supplied is a practical measure of the efficiency. It has become customary to state, not the number of C.P. produced per watt supplied, but the number of watts required to produce 1 C.P., and this latter quantity is generally termed the efficiency. It is an unfortunate term, but it is almost universal. When it is stated that the

[1] Much of the research on carbon lamps was done in this country; most of that on metal filaments has been carried out in Germany and America.

efficiency of a certain lamp is 4 watts per C.P., it is meant that 4 watts are required per C.P. produced, when the lamp is supplied with the voltage for which the maker has graded it. If it were supplied with a higher voltage, and therefore, of course, more power, the efficiency would be increased (or the watts per C.P. diminished), because the temperature of the filament would be higher. Now it has been found by long experience, that if a reasonable life (1000 hours) has to be obtained, it is not possible with a carbon filament lamp to procure much more than 1 C.P. for each 4 watts supplied. If carbon lamps are graded to be more efficient it will be found that as a rule the life is less than 1000 hours. This is the case with the so-called high efficiency lamps which were introduced a few years ago. The chief reason that carbon lamps are being largely superseded, is that other lamps can be produced, which, while maintaining the same life, will have about three times the efficiency. Another disadvantage of carbon lamps is that they are very sensitive to voltage variations. This is because carbon has a negative temperature coefficient. A 1 per cent. increase in voltage with a carbon lamp, leads to more than 2 per cent. increase in power absorbed, whereas with a metal lamp the same increase in voltage causes less than 2 per cent. increase in power. Hence in the latter case, the C.P. is not increased so much as in the former. The C.P. of a carbon lamp is proportional to about the sixth power of the voltage; with a tungsten lamp the C.P. varies as the fourth power.

Nernst Lamps.—This lamp was the invention of a German professor, and was introduced about 1895. The filament or glower is a short, thick rod, composed of a mixture of oxides, thoria being a large constituent. The specific resistance of the mixture is very high at ordinary temperatures; in fact, it may be regarded almost as an insulator, but when heated to about 500° C it begins to conduct. Stated in another way, the temperature coefficient is negative and large, and this necessitates the use of two auxiliaries with the lamp. Firstly, in order to make the glower light up, it must be given a preliminary heating. This is generally done electrically by means of a heating grid placed above the glower. Secondly, there has to be connected in series with the filament a spiral of iron wire. The object of this device is to make the lamp electrically stable. Iron, like all pure metals has a positive temperature coefficient, and this serves to neutralise, to some extent, the large negative coefficient of the glower. At the present time there are very few Nernst lamps being installed, and many are being taken out and replaced by

metal lamps. The complication caused by the iron resistances and the heating coil partly account for this; also the lack of uniformity in the life of the glowers. The Nernst lamps are graded at about 2 watts per C.P. They are intermediate in efficiency between carbon lamps and tungsten lamps, and since the latter are free from complications and more efficient, they have to a large extent taken the place of the Nernst. Nernst lamps are very good for illuminating mirrors, for galvanometers, and for similar work, because the filament is so broad.

Osmium Lamps. — Lamps with filaments of the metal osmium were next put on the market. They were remarkably efficient (1¼ watts per C.P.), but very expensive on account of the difficulties of manufacture and the cost of the material. The 110 volt lamps had 4 V-shaped filaments connected in series inside the same bulb. The material cannot be drawn into a wire, and the filaments were produced by a squirting process. Another difficulty was due to the poisonous character of the metal. The lamps were very fragile, and are not now being sold.

Tantalum Lamps. — Messrs Siemens & Halske succeeded in producing lamps with tantalum filaments about 1904 after a great deal of painstaking research. Unlike osmium, tantalum may be drawn into a filament, and this renders the manufacture much simpler. The specific resistance of tantalum metal is lower than carbon at the working temperature. Consequently, the filaments have to be both longer and thinner than a carbon filament of the same resistance. For example, the filament of a tantalum lamp has to be 2½ times the length and ¼ the diameter of the carbon filament for the same voltage and C.P. The length of the filament of a 110 volt, 25 C.P. lamp is 65 centimetres and the diameter 0.047 millimetres, whilst for a carbon filament of the same candle-power, the figures are 25 centimetres and 0.18 millimetres respectively. Tantalum lamps are rated at different values according to the purpose for which they are required. Lamps which are likely to experience vibration (*e.g.*, in traction work), are graded at 1.8 watts per C.P., while lamps for ordinary purposes are run at about 1.6 watts per C.P. The construction of the tantalum lamp renders it very suitable for cases where there is likely to be excessive vibration.

Tungsten Lamps.—Tungsten is not an uncommon metal, and has for years been employed in the manufacture of self-hardening tool steel, but only recently has it been obtained in a pure state. The pure metal is exceedingly brittle, and for many years baffled all attempts to draw it into wire. The early lamps

were made either by the squirting process or by a replacement process starting with a carbon filament as a base.

At the present time a large number of tungsten lamps have filaments produced by drawing. One method is to alloy the tungsten with a small percentage of nickel, draw this alloy into the required shape, and afterwards volatise the nickel. But it has been found possible, by working the metallic tungsten in various ways, to render it more plastic, so that it may be drawn. The details of this process—which was developed at the works of the General Electric Co., U.S.A.—have not been made public at the time of writing.

The filament for a 5 C.P. 110 volt tungsten lamp is 0.01 millimetre diameter and 33 centimetres long.

Tungsten lamps are sold both in this country and abroad, under a great variety of trade names, but the article is very much the same in all cases. They are usually rated at from 0.9 to 1.2 watts per mean horizontal C.P. They are not so sensitive to changes in voltage as carbon lamps, but overrun lamps blacken just as carbon lamps do. The temperature of tungsten filaments is said to be about 2400° C.

The most recent developments at the time of writing (1913) are lamps with tungsten filaments, the filament being placed in an inert atmosphere instead of the usual method of exhausting the bulb to a high vacuum.

The presence of the gas seems to prevent the metal from volatilising, and enables the filament to be run at a higher temperature than is usual with tungsten lamps. In spite of the conduction of heat by the gas from the filament to the glass the efficiency of the lamps is higher than that of the tungsten lamps with exhausted bulbs. The makers claim an efficiency of 2 C.P. per watt and a life of 1000 hours. The lamps are not at present made in smaller units than 200 C.P., and on account of the large current to be led in and out the Edison screw cap has been adopted. The overall length for a 600 C.P. lamp is about 12 inches. Fig. 49 is a view of one of these lamps.

Arc Lamps.—On p. 98 some of the general properties of an arc produced between carbon electrodes were considered. The fact that the positive crater is the hottest part of an arc accounts for its being the chief source of light. In an open arc supplied with continuous current, about 90 per cent. of the total light emitted comes from the end of the positive carbon. For this reason, except where arc lamps are used for inverted lighting, the positive electrode is placed above the negative. Further, since the positive carbon is so much hotter, it burns away at a greater rate, and in order to have the two carbons burning the same number of inches per hour, it is usual

to make the negative carbon about half the diameter of the positive. This has the further advantage that the light cut off by the negative is reduced.

In order to decrease the rate of combustion of the electrodes in arc lamps, the arc may be surrounded by a globe, which, while not being absolutely air tight, very much reduces the

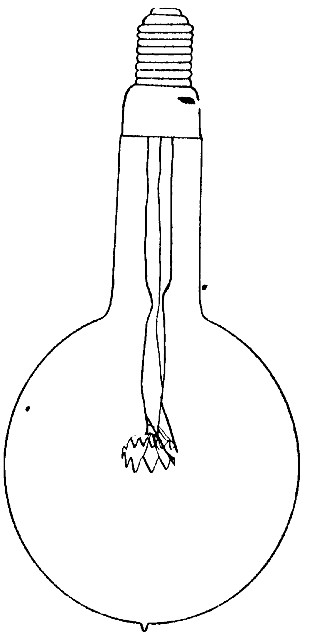


Fig. 49. TUNGSTEN "½-WATT LAMP."

circulation of air. Such a lamp is named an enclosed lamp, and one in which no attempt is made to interfere with the natural rate of burning, is called an open lamp. The appearance of the carbon ends in both types is shown in Fig. 50.

In many cases the electrodes in an arc lamp are arranged co-axially, but sometimes they are inclined at an angle of about 20°. This last arrangement is the one generally adopted in flame lamps. The positive carbon for continuous current lamps is "cored." The carbon rod is, in the first instance, made hollow, and afterwards the space is filled in with carbon of a softer variety. The advantage of using a cored positive, is that the arc is maintained in the centre more readily. In certain

types of lamps the arc is coloured by some metallic salt, which is supplied by placing it in the core of the carbons, from whence it passes into the arc. To distinguish them from ordinary carbons, these are called *impregnated* or *salted* carbons. The effect of these salts is to colour the arc, just as salt introduced into a bunsen flame will give it a characteristic colour, and what is more important, the amount of light given out by the arc is enormously increased.

The illuminating power of an arc lamp is usually expressed

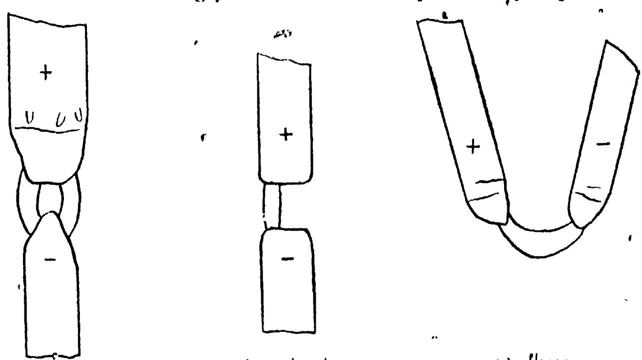


Fig. 50.

APPEARANCE OF ARCS.

by stating the mean candle-power in all directions below a horizontal plane passing through the arc. This is called the mean hemispherical candle-power, because it is only the lower hemisphere which is considered.

Below are given average figures for the mean hemispherical candle-power obtained per watt:—

Open.	Enclosed.	Flame.
1—1.5	0.5—0.7	2—5

Arc Lamp Mechanisms.[1]—For certain classes of work, such as lanterns, it is possible to adjust an arc by hand, the carbons being fed forward at intervals to prevent the arc becoming too long. But in the great majority of cases, where an arc is used for lighting purposes, it is necessary to provide a mechanism which will render the lamp entirely automatic.

[1] No attempt is made here to describe all the various types of mechanisms which have been introduced. It is far better for the student to examine the lamps for himself.

This mechanism has both to strike the arc and feed the carbons forward. In some lamps more than one pair of carbons are provided, and then the mechanism has the additional duty of substituting fresh carbons when one pair is consumed.

Except in a few cases, the electro-magnetic principle is made use of in arc lamp mechanisms. Lamps have been manufactured in which the necessary regulation was brought about by the expansion and contraction of a strip through which the main current was passed, but these lamps have not been altogether successful.

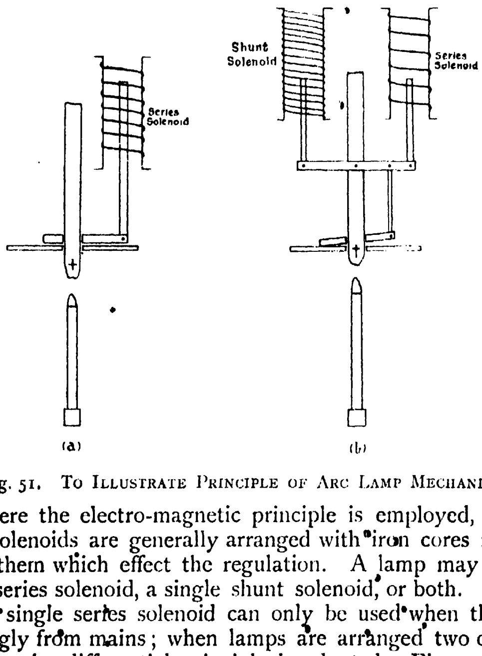


Fig. 51. To Illustrate Principle of Arc Lamp Mechanism.

Where the electro-magnetic principle is employed, one or more solenoids are generally arranged with iron cores moving inside them which effect the regulation. A lamp may have a single series solenoid, a single shunt solenoid, or both. Lamps with a single series solenoid can only be used when they are run singly from mains; when lamps are arranged two or more in series, the differential principle is adopted. Fig. 51 shows diagrammatically how an arc may be adjusted with (*a*) series, (*b*) differential mechanisms. In each case, there must be an equilibrium established between the pull due to the mechanism and some other force such as gravitational attraction when the arc is of the desired length. For example, in (*a*), Fig. 51, the superior weight of the top carbon holder will keep the carbons in contact till the current is switched on. In the case of a series lamp, a little thought will show that the action of the

solenoid must be to lengthen the arc, and when the upward pull produced by the solenoid balances the downward pull due to gravity, the current and length of arc should have the desired value.

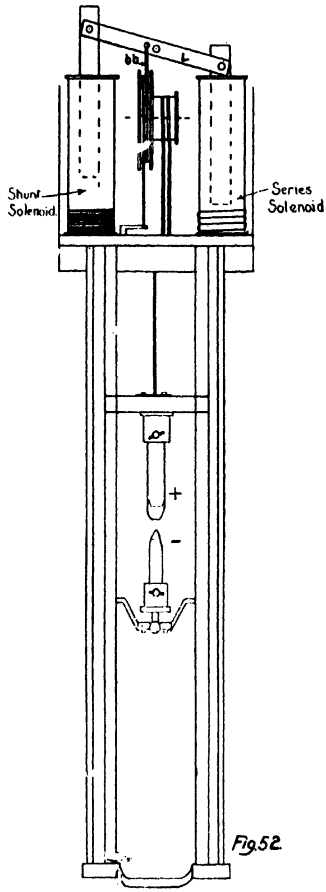


Fig. 52.

DIAGRAMMATIC VIEW OF MECHANISM IN CROMPTON ARC LAMP.

As an example of a mechanism such as is used in an open arc lamp, we may mention that employed by Messrs Crompton and Co. of Chelmsford. A diagrammatic view to explain the

working of this lamp, is given in Fig. 52. There are two solenoids, a series and a shunt, provided with the usual plungers. These plungers are connected with a rocking lever, L, and attached to this, at a point about 1 inch from its pivot, is the flexible brake band *bb*, which, with its rubber sheath, grips the brake wheel. When the core is pulled down into the shunt coil, the wheel is freed and the carbons fall together. The current passing round the series coil pulls the lever over, raises the band which first grips and later revolves the brake wheel. This separates the carbons, and the arc is struck.

Flame Arc Lamps.—At the present time the most important class of lamps are the flame arcs. Some of the characteristics of a flame arc have been mentioned on p. 110. Apart from the impregnating of the carbons, these are made smaller in diameter than those in an ordinary lamp for the same current, and, as a rule, burn away at the rate of about 2 inches per hour; also positive and negative carbons are made nearly the same size, *see* Fig. 50. Now an arc lamp is of very little use unless it will burn ten hours without retrimming. Hence, allowing 2 inches for the spare ends, which cannot be burned, the above condition necessitates the employment of carbons 22 inches long. The cost of production of such long carbons is much higher than that of short ones, and the breakages are more numerous. Also the length of the lamp has to be increased, which makes it unsightly. For these reasons, a large amount of attention has been paid during the last few years to the production of a magazine lamp, that is one which holds a large number of pairs of carbons, and is provided with a mechanism for inserting them one after the other. Several lamps of this class are on the market, and have proved a distinct success.

In most cases, the inclined arrangement of holding the carbons is adopted, but the carbons may be arranged co-axially.

In Fig. 53 are shown two sectional views of the "Metroflam lamp—a flame arc lamp manufactured by Messrs Johnson and Phillips. The lamp is regulated by means of two shunt and one series solenoid. The series coil A and the shunt coil I work in opposition, and provide a differential regulation. The third coil E is to move the carbons downwards.

The positive and negative carbons are held in two magazine which are inclined to each other. Two endless chains shown in the left-hand figure pass down the centres of the magazines. Each chain is provided with two projecting pins, which are on opposite sides of the chain, and at diametrically opposite points on it. Half of the carbons in one magazine are on the right and half on the left (*see* right-hand view), and one of the pins

on the chain moves a carbon down from the right side, while the other pin will propel a carbon on the left-hand side.

When current passes round the solenoid E the core F is

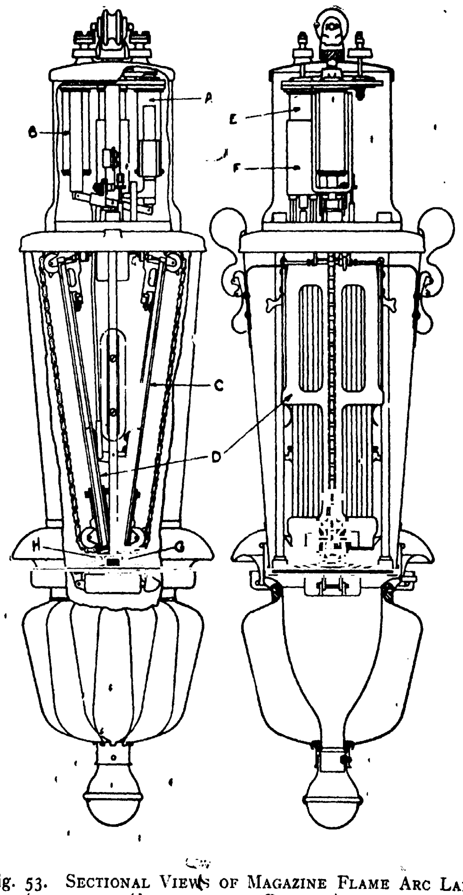


Fig. 53. Sectional Views of Magazine Flame Arc Lamp (Johnston and Phillips).

pulled up, and this operating through a suitable gearing slightly revolves both chains in such a direction that the inner halves of both move downwards and pull the particular pair of carbons which are in service down slightly. But when the core F is

pulled up, the circuit of the coil E is broken, and the core drops again. Thus an up and down motion continues till the arc is struck. When this takes place the rocking lever, which is connected with the cores which move inside coils A and B, is pulled over by the series coil. This lever pulls up a rod which opens the switch circuit with the coil E. As the positive and negative carbons burn away they continue to be fed forward until the pin on the revolving chain arrives at the lower wheel. The short ends are left in the nozzles G and H, and as the arc becomes long the chains continue to revolve, and this time the pin on the other side engages with a carbon on the other side of the magazine. This second pair continue to be fed forward till they touch. When the new pair touch, the voltage across the other arc goes down, and thus at the same instant that the new arc is struck, the old one is extinguished. This is an extremely ingenious principle invented by Mr Brockie, and is one of the good features of the lamp. As a result there is no interval of darkness, such as occurs in other magazine lamps. This interval may be from fifteen seconds to one minute, and if it occurs at a critical time may have an important result.

The magazines, C and D, hold from 12 to 16 pairs of carbons according to the size of the lamp. The diameter of the positive carbon is slightly greater than that of the negative. For instance, in a 10-ampere lamp the positive is 9 millimetres, and the negative 8 millimetres diameter.

Vapour Lamps.—One of the most successful of this class of lamps is the mercury vapour lamp, invented by Mr Cooper-Hewitt. The main features are a long glass tube about 1¾ inches in diameter, provided with electrodes at either end and carefully exhausted. The positive electrode is of iron, and the negative is mercury, which normally is contained at the right-hand side of the tube. Connected in series, but external to the lamp, is a ballast resistance.

The tube is normally nearly horizontal, and pivoted about an axis at right angles to its length. In some lamps the tube is rocked by an automatic mechanism, while in others there is a chain attached to one end so that the tube may be tilted by hand. In any case, to start the lamp, it is necessary after closing the switch to tilt the tube and allow the mercury to bridge across from one electrode to the other. When the arc is struck, the tube is allowed to return to its normal position. The whole tube fills up with a greenish-blue light with which most of us are familiar. In spite of the objectional colour, the lamp has several advantages. The efficiency is certainly higher than that of an ordinary arc lamp, though not so

high as that of a flame lamp. On the other hand, the lamp requires no attention, and there are no carbons to buy.

Quartz Lamps. — The efficiency of the mercury lamp is limited by the fact that the glass will soften if too much current is passed through the tube. By making the tube of quartz, however, this difficulty may be overcome to some extent. Quartz lamps are constructed in which the tube is 3 inches long and $\frac{5}{8}$ inches diameter, which give over 1000 C.P. Unlike glass, quartz is transparent to ultra-violet light. This is a great advantage when the light from the lamp is required for printing in photography or similar processes. For purposes of general illumination, however, the lamp must be mounted inside a glass globe, either transparent or opalescent, so that the ultra-violet rays may be absorbed, otherwise very serious results may happen, particularly to those whose eyes have any tendency to weakness.

The Moore Tube Lamp.—We shall conclude this chapter with a brief reference to a system of lighting introduced by Mr MacFarline Moore. This arrangement may perhaps be regarded as an extension of the principle adopted in the Cooper-Hewitt lamp. A tube about 2 inches in diameter is mounted in a room about a foot from the ceiling, and usually follows round the walls. The tubes are generally arranged in duplicate in case of accident. As in the lamps just described, the current passes through a vapour, which is therefore illuminated, but instead of mercury vapour, carbon dioxide[1] or nitrogen gas is employed. With carbon dioxide the colour of the light is whitish-blue, and the author has seen these lamps used with success in a velvet warehouse, where it is important that there should be no distortion of colour. The tube being so much longer than a Cooper-Hewitt tube, a high voltage is necessary to send the current through, and for this purpose an alternative current supply is required. The necessary high pressure is obtained by means of a statical transformer. For a tube 30 metres long the pressure required is about 7000 volts. An electrically operated valve is used to keep the pressure of the gas at the best value, as this, of course, changes with temperature. From the point of view of economy, either in first cost or in working, Mr Moore's arrangement is inferior to metal lamps; its great advantage lies in the equal distribution of the light and the absence of shadows. Any one who has seen the lamps working will have been struck with the splendid imitation of daylight and the remarkable even diffusion.

[1] Remarkable results have been obtained by Claude using tubes filled with neon. It is stated that an efficiency of 2 C.P. per watt has been obtained as against 0.58 C.P. per watt with nitrogen tubes.

EXAMPLES

(1) If a glow lamp takes $3\frac{1}{2}$ watts per candle, and a gas burner gives 3 candles per cubic foot of gas burned per hour, what must be the price of a B.O.T. unit, so that the cost of electric lighting may be the same as that of gas lighting with gas at 2s. 9d. per 1000 feet, the cost of lamps, fittings, wiring, etc., being excluded? (C & G) (E).

(2) What is meant by a flame arc lamp? How do those lamps differ electrically and optically from an ordinary arc lamp?

(3) The diameter of the filament of a 110 volt "Osram" lamp is $\frac{1}{30}$ millimetre and the length 50 centimetres. Calculate the specific resistance of the material if the lamp takes 40 watts. What would the resistance of the filament for a 220 volt lamp have to be for the same candle-power?

(4) What are the relative merits of arc lamps and metal lamps for interior lighting? What objection could be urged against flame lamps in particular for this purpose?

(5) Explain the chief differences between carbon glow lamps and lamps with metal filaments.

A consumer originally provided with carbon lamps requiring 4 watts per C.P. replaces them by metal lamps requiring $1\frac{1}{2}$ watts per C.P. He has fifty 20-C.P. lamps, and uses them on an average 20 hours per week. If he pays 3d. per unit for his current, how much will he save per week by the change, neglecting cost of lamps?

(6) In what respects optically and electrically do the newer kinds of glow lamps with metal filaments differ from the older kinds with carbon filaments? How are their luminous outputs, their energy consumption, and their efficiencies affected by a lowering of the voltage below, or a raising of the voltage above, the normal value for which the lamp is intended? (C & G) (O).

CHAPTER XIII

PRIMARY AND SECONDARY CELLS

Primary Cells; Disadvantages of the Simple Cell.—In chapter i. the elementary facts concerning a simple voltaic cell were dealt with.

The copper-zinc cell described there, although it has the advantage of extreme simplicity, is never used in practice. In the first place, the zinc, unless it be extremely pure, is dissolved away by the sulphuric acid when the cell is sending no current. Secondly, the E.M.F. of the cell is not constant. If the E.M.F. of such a simple cell be determined by an accurate method, it will be found to be just above 1 volt when the cell is freshly made up, but after the cell has been sending current for some time, the E.M.F. will fall. This effect is due to the deposition of bubbles of hydrogen upon the copper plate. These set up a counter effect E.M.F., and reduce the actual E.M.F. of the cell. In this condition, the cell is said to be *polarised.* Various types of primary cells have been proposed from time to time, but only two or three have come largely into use.

The Daniell Cell.—This cell is similar to the simple cell invented by Volta, but is modified in order to avoid the polarisation effect. The elements are, as in the simple cell, zinc and copper, and the exciting fluid either dilute sulphuric acid or zinc sulphate. The copper plate, however, instead of being placed in the acid, is immersed in copper sulphate, contained in a vessel made of unglazed earthenware. This material is adopted, because, while it prevents the liquids mixing to a great extent, its pores are permeated by the solution, and the current is able to pass through. Fig. 54 shows a double pattern of Daniell's cell made by the General Electric Co. The E.M.F. of Daniell's cell is about 1.07 volts, the exact value depending upon the degree of concentration of the solutions.

The action of cell is as follows:—The zinc dissolves in the

sulphuric acid, and hydrogen is liberated as in the simple cell. Instead of the hydrogen being deposited on the copper plate, it attacks the copper sulphate, and sulphuric acid is again formed, while metallic copper is deposited on the copper plate. The copper sulphate solution thus prevents the cell becoming polarised, by removing the hydrogen as quickly as it is liberated. For this reason the copper sulphate is termed a depolariser. This form of cell has been largely used for telegraph work on

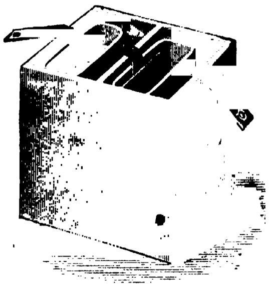


Fig. 54. Double Pattern Daniell Cell.

account of its extreme constancy. In working, the zinc dissolves and must be replaced, while copper is deposited upon the copper plate, causing the copper sulphate solution to become weakened. Crystals of copper sulphate are sometimes placed in the cell to replace the salt which is taken out.

The Leclanché Cell.—This is the most familiar of all primary cells, and the most easily maintained. Various modifications of the original pattern have been invented, but this is still widely used. The general appearance is shown in Fig. 55, which has been made from a block kindly supplied by the General Electric Co. The negative electrode is a rod of zinc, to which some mercury has been added, and this is placed in a solution of ammonium chloride (salammoniac). The porous vessel contains a rod of carbon which forms the positive pole. On the top of the rod a cap of lead is cast, and to this a terminal is fixed. Packed round the carbon rod is a mixture of powdered carbon and manganese dioxide (black oxide of manganese). The latter substance plays the same part as the copper sulphate in the Daniell cell, and causes slow depolarisation.

When current is taken from the Leclanché cell, the E.M.F. rapidly falls, but the cell recovers when left standing. For this reason, the cell is chiefly used for purposes in which an

intermittent current is required, such, for example, as domestic signalling and telephone work. The E.M.F. on open circuit is about 1.55 volts, and the internal resistance usually from ½

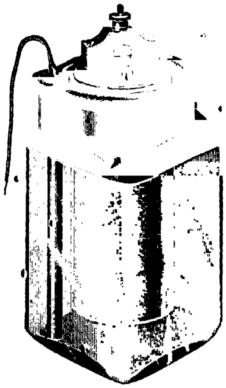


Fig. 55. Leclanché Cell with Porous Pot.

to 1 ohm, depending on the size. The capacity of the "two pint" size is in the neighbourhood of 15 ampere-hours. A modification of the pattern just described, known as the "Carsac" Leclanché, is illustrated in Fig. 56. The chief

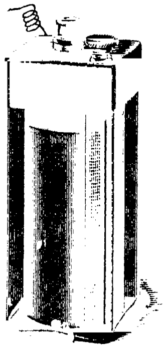


Fig. 56. Leclanché Cell—Carsac Pattern.

difference lies in the absence of the porous pot, the place of which is taken by a canvas sack. The effect of this is to give a much lower internal resistance, which in the cell illustrated is about $\frac{1}{10}$ ohm.

The Cadmium Cell.—One of the most important applications of the primary cell is as a standard of E.M.F. Various patterns have been devised for this purpose, but the cadmium cell has now practically superseded the others.

The elements in this case are mercury and an amalgam of cadmium and mercury, which are placed in the upright portions of an H tube. Fig. 57, which shows the essential parts of a cell made by H. Tinsley & Co., will explain the arrangement. The cell is hermetically sealed, and great precautions are taken to ensure that the metals and the crystals are pure. If carefully made up, the E.M.F's. of different cells will agree to about one part in 10,000.

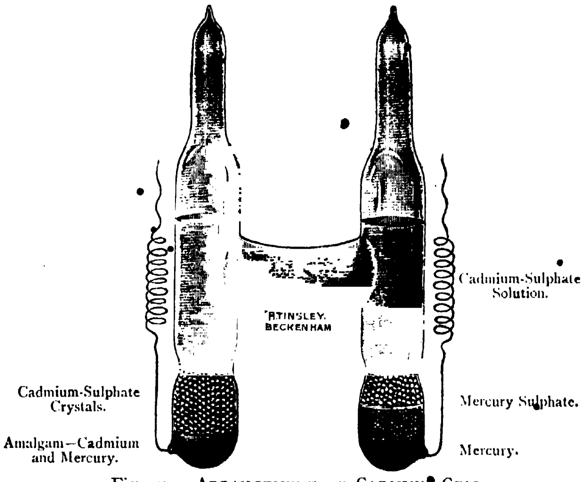


Fig. 57. Arrangement of Cadmium Cell.

The E.M.F. at 15° C is 1.0184 volts, and the variation with temperature is extremely small. This is an important consideration where great accuracy is required.

Secondary Cells.—When a primary cell is in use, the negative electrode (usually zinc) dissolves away and can only be recovered from the solution formed by a metallurgical process. For this and other reasons mentioned below, a type of cell which may be restored to its original condition by passing a current through it, is largely used in engineering work. In order to charge the cell, a current is passed through it in a direction opposite to that of the current produced by the cell itself. Such cells are termed secondary cells or accumulators.

Practically all the secondary cells in use at the present time are made with lead plates, the electrolyte being dilute sulphuric acid. The lead accumulator was invented by Planté, and both in Planté's original form and in many of the modern types, the plates are sheets of pure lead placed in a solution of dilute acid. The plates are of such a shape that, whilst being strong, they expose as large a surface as possible to the acid. The student should obtain two clean lead plates, place them in acid, pass a current through, and notice the result produced. It will be seen that while one of the plates, that at which the current leaves the solution, is unaltered, the other (the +) becomes a chocolate colour. This coloration is due to the formation of dioxide of lead $Pb\ O_2$. If a voltmeter be connected across the plates, it will be found that on charging, the P.D. between them is considerably above 2 volts (perhaps 2.4). When the charging ceases, the voltmeter will continue to indicate about 2 volts.

The experimental cell may now be discharged by connecting it to some kind of a circuit. When current is allowed to flow and the cell discharges, the voltage will be found to remain fairly constant at about 2 volts, but after some time will have fallen to 1.8, and when that stage is reached, the cell is very quickly discharged.

The length of time which a cell will take with a particular current, to charge or discharge, depends on its "capacity." The capacity is directly proportional to the area of the plates, and the important problem for the cell manufacturer is to obtain a high capacity and strong plates without getting undue weight. It is, of course, unfortunate from this point of view, that the density of lead is so high, but its other properties outweigh this disadvantage. A modification of Planté's cell was introduced by Faure, who adopted a lead grid instead of a plate, and filled in the interstices with a paste made of lead oxide[1] and sulphuric acid. This is called a pasted plate, and the capacity is obtained chiefly from the pellets of paste; at any rate, this is so when the plates are new. Various forms of grids have been invented to keep the paste from falling out and to prevent buckling. Sometimes cells are made with Planté positive plates and pasted negatives.

Chemical Action.—The chemical actions which take place in an accumulator are complicated, but the following represents roughly what happens: At charging, the negative plate is reduced by the hydrogen evolved to pure lead, while the positive is oxidised to lead dioxide $Pb\ O_2$. On discharging, the lead at the negative is changed into lead sulphate $Pb\ SO_4$, and

[1] Litharge may be used for the negative and red lead for the positive.

the lead dioxide at the positive is reduced to lead sulphate. During discharge, water is formed, and the density of the solution is therefore lowered. If the density be known when the cell is fully charged, the state of charge may be approximately ascertained by means of a hydrometer placed in the electrolyte. For example, if the density fully charged is 1.21, that at discharge will be about 1.19.

Arrangement of Plates.—Fig. 58 shows the section of the plates in a large accumulator, manufactured by the Tudor

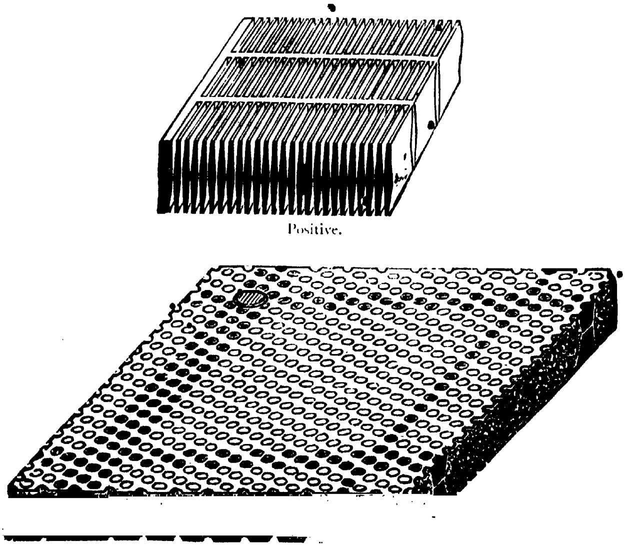


Fig. 58. SECTION OF PLATES OF TUDOR ACCUMULATOR.

Accumulator Co. A complete cell, manufactured by the same firm, is illustrated in Fig. 59.

There is always in an accumulator one more negative than positive plate. This arrangement is adopted in order to utilise both sides of the positive plate, and thus diminish buckling. With plates of the pasted type, a considerable clearance is left between the bottom of the plates and the bottom of the vessel, the object being to prevent any "shorting," due to pellets of paste which have fallen down. The plates are generally kept apart by means of a glass separator. The plates in large cells are burned on to heavy lead lugs—

the positives to a lug on one side, and the negatives to a lug on the other. The cells also are connected together by this method.

Charging and Discharging.—The difference of potential between the terminals of an accumulator depends on its state of charge, and also upon the value of the charging and discharging current. A graph showing the P.D. at various intervals during the charge or discharge is very useful, and is known as a charge or discharge curve.

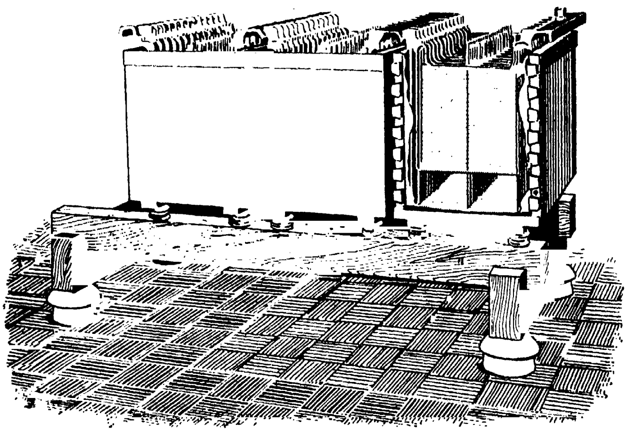
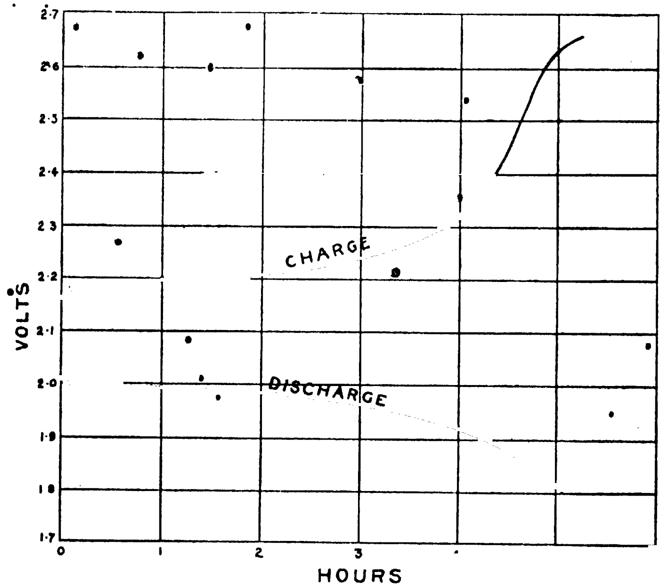


Fig. 59. ARRANGEMENT OF CELLS.

In Fig. 60 are shown typical charge and discharge curves for a Tudor accumulator. When the charging has proceeded for some time, and the E.M.F. has risen to about 2.3, it will be noticed on inspection that the electrolyte is milky. This is due to innumerable particles of gas, which at the end of the charge are not absorbed by the plates, and rise through the liquid, giving it the whitened appearance. It is an indication that the charge is approaching completion. In order to give good results, accumulators need very careful treatment. They must not be charged or discharged too rapidly, and, above all, the discharge should always be stopped when the E.M.F. has fallen to 1.85 volts per cell. Most accumulators are made to be charged or discharged in about 6 to 8 hours. The cells used in generating stations are required to be discharged in much shorter periods, and the makers supply cells with specially strong plates, which may be discharged in 2 hours without

damage. The capacity, however, is less than if they were discharged more slowly.

Uses of Accumulators.—The most important application of accumulators is to central station work. The battery is charged during the day, or when the load is light and may be discharged in the evening or at times of heavy load. Very considerable



CHARGE AND DISCHARGE CURVES FOR ACCUMULATOR.

economies may be effected by employing a battery in this way, but the initial cost and renewals of a battery are very high. Accumulators are also largely used for portable appliances, for producing electric ignition in internal combustion engines, and for miners' electric lamps. They are used for driving the motors in electric automobiles and submarines, and sometimes in electric trams. A reference to Fig. 60 will show that the E.M.F. of an accumulator is very constant for several hours; for this reason they are of very great use in testing, and are largely used in calibrating and in standardising work. Accumulators are now largely used in telephony.

EXAMPLES

(1) Describe the Leclanché cell, and say what changes occur in it when its circuit is closed. How many such cells would you require for a 600-volt battery? (C & G) (E).

(2) Describe briefly the construction and action of an accumulator. What are the chief industrial uses to which the accumulators are put?

(3) What are the advantages of using accumulators at an electric light central station? What type of accumulators would you adopt for this purpose, and why? (C & G) (O).

(4) To what point should accumulators be discharged? What is the suitable density of the acid that should be used in them? How would you test a set of accumulators to discover whether they were fully charged? What is the particular harm that results if accumulators are left long in a discharged state? (C & G) (E).

(5) A cadmium cell which is certified to give 1.018 volts is connected to a good voltmeter, and the reading obtained is a small fraction of a volt. Explain this result.

(6) A "chloride" accumulator used in connection with a miner's electric lamp weighs 2¾ lbs. and is connected to the lamp for 9 hours. The lamp takes 2 watts, and during the shift the voltage falls from 2.05 to 1.85. Assuming the accumulator to be discharged at this lower voltage, determine its "ampere-hour" and its "watt-hour" capacity. Calculate also the watt-hour capacity per lb.

CHAPTER XIV

ELECTRICAL INSTRUMENTS AND METERS

INTRODUCTORY.—In this chapter we shall endeavour to outline the principles underlying instruments used for measurements in continuous current work.

It is convenient to classify instruments as follows:—

(1) Indicating.
(2) Recording.
(3) Integrating.

An instrument of the first class is one which, when read, will tell the value of a particular quantity (*e.g.*, current), at the moment of taking the reading. Its indication has, or should have, no relation whatever to what has taken place in the circuit previously. The chief examples of this class are voltmeters for indicating the P.D. between two points of a circuit, amperemeters or ammeters for indicating the current, and wattmeters for indicating the power passing into a circuit. If the quantity being measured be fluctuating rapidly, the instrument will indicate a mean value.

Recording instruments, while they may be consulted to tell the value of the quantity being measured at an instant, are designed to leave a permanent record on a chart of some kind, showing the magnitude of the quantity along a time scale. The third class of instruments, known as "integrating," tell us the product of a quantity (generally current or power) and time. They are used as a basis for charging for electrical energy supplied, in the same way that a gas meter is used for telling the consumption of gas. An instrument which by its reading tells us the amount of energy—the number of watt hours or kilowatt hours—which has passed into a circuit during a particular interval, is called a watt-hour meter, or an integrating watt meter. It must not be called a watt meter, which is an indicating instrument, nor on the other hand is it a recording watt meter, although this term is sometimes applied

Indicating Instruments. — In C.C. circuits, the quantities which have to be measured are voltage and current. It is, of course, possible to measure power in a C.C. circuit by means of a watt meter, but this is not often done. With the exception of electro-static instruments which are not described here since they are chiefly used for alternating current measurements, voltmeters measure the P.D. between two points of a circuit by measuring the current which this P.D. will produce through another circuit, viz., the voltmeter. Now Ohm's law tells us that in a circuit of constant resistance $C \propto V$. Thus the assumption is made in all voltmeters that the resistance is always constant, or rather that the resistance is always the same for a particular value of current passing through the instrument. Any change in resistance such as that produced by change in temperature will give rise to error. When a quantity has to be measured, it is most important that the means chosen should not alter the value of the quantity in question. In the case of a voltmeter connected to measure the P.D. between two points in a circuit, if connecting the voltmeter is to produce the minimum of disturbance, the resistance of the voltmeter must be high. For a similar reason, the resistance of an ammeter must be kept as low as possible, because the larger it is, the more will it reduce the current when placed in circuit. It will easily be understood that if the power to be wasted in a voltmeter is to be small, it should have a high resistance, while for the same reason that of an ammeter should be low.

It follows from what has already been said that both voltmeters and amperemeters must make use of one of the effects of a current in their working. In most cases it is the electromagnetic effect which is adopted, purely on account of convenience. Instruments depending upon the heating effect of a current, measured by the expansion of a wire, are called 'hot-wire meters, and while possessing some advantages for measuring alternating currents, they have no place at all in continuous current work, and are never used in modern practice.

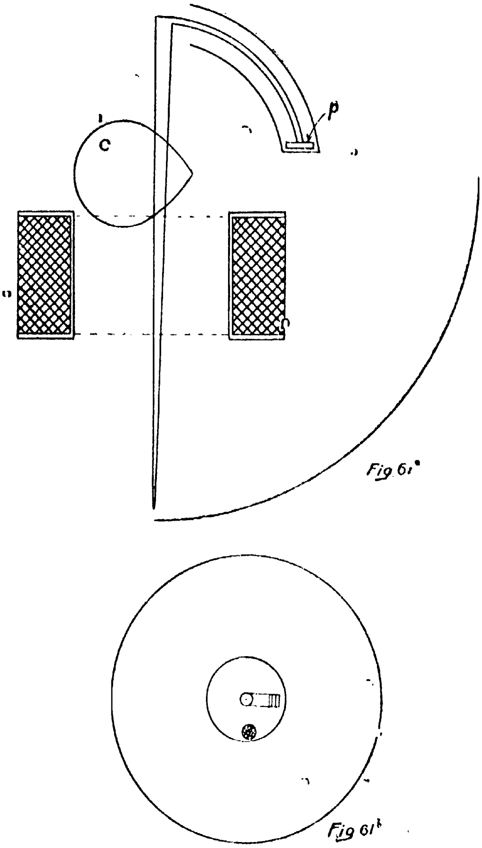
Electro-magnetic Instruments.—Electro-magnetic instruments are of two classes—

(1) Moving iron or soft iron.
(2) Moving coil, polarised.[1]

In the first group of class (1) some form of solenoid is adopted, and a needle of soft iron is attracted into this solenoid by a force which will depend upon the strength of the current

[1] There is another class of moving coil instruments known as the dynamometer type. They are chiefly used in alternating current circuits.

flowing through the coil. In another pattern, known as the repelled iron type, there are two iron plates placed inside the solenoid, one stationary and the other movable. When current flows round the solenoid, these plates become magnetised



To ILLUSTRATE THE ACTION OF MOVING IRON INSTRUMENTS.

and repel each other, the movement being registered by the deflection of the pointer. Fig. 61 illustrates these two principles. *a* represents the essential parts of an instrument made by Siemens Bros. The pear-shaped piece of soft iron (*c*) is flat and mounted rigidly on the horizontal pivot. It is attracted

into the solenoid by a force depending upon the strength of the field produced. If the instrument be an ammeter, this solenoid will be wound with a few turns of thick wire or strip, the larger the current, the greater the area of the wire and the fewer the number of turns. For a voltmeter, the coil would be wound with very fine silk-covered wire. The same mechanism is used in both instruments, and the number of ampere turns may be the same in the two cases.

Fig. 62 illustrates an example of the repelled iron type manufactured by Nalder Bros., while Fig. 61*b* is a section through the solenoid.

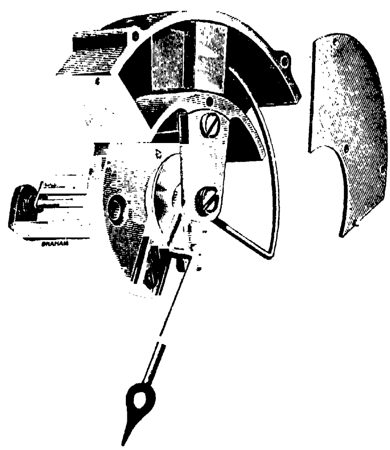


Fig. 62. General View of Nalder's Moving Iron Instrument.

In this instrument, the fixed plate consists of one or more pieces of iron wire, while the moving plate takes the form of one or more strips of soft iron of rectangular section. The moving plate is mounted on an arm connected to a horizontal spindle pivoted between jewelled centres.

The two iron plates being inside the same coil are similarly magnetised which ever way the current flows. If the direction of current be clockwise, the ends facing us will have south poles; if the current flows anti-clockwise, the north poles will be presented to us. Notice that as the pointer moves over the scale, the plates become further apart, and thus the repulsion for a particular strength of pole will diminish. A little consideration will show that with both of these instruments the reading is independent of the direction of the current.

The two instruments described above have different methods of control. In the Siemens' instrument, when the pointer moves over the scale, the counterweights (not shown) are moved further from the axis of rotation, and since they are pulled down by gravitational attraction, a restoring torque is produced which increases with the deflection. The control in this case is said to be "gravitational."

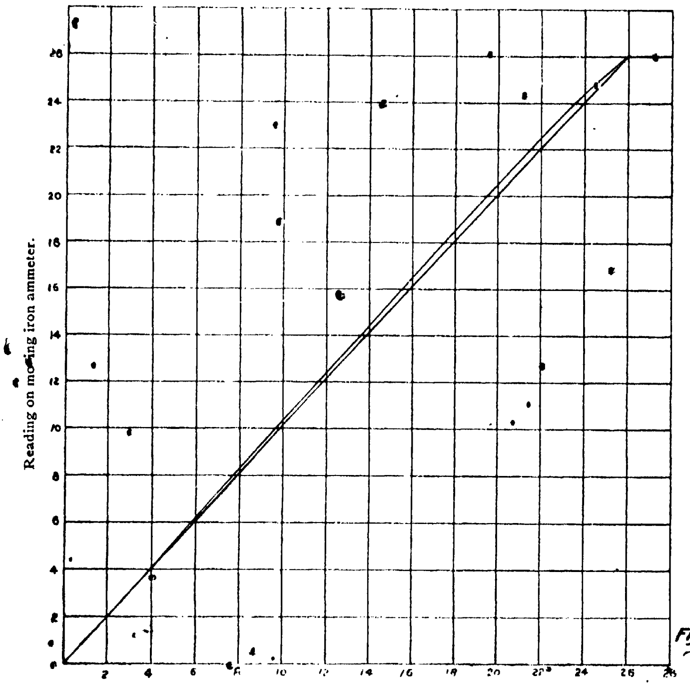
In order to prevent the pointer of an instrument from swinging about the position of equilibrium, a damping device is employed. This is an arrangement which, while not adding any friction to the moving parts of an instrument, prevents rapid motion, and causes the pointer to come quickly to rest. Although this is sometimes omitted on cheap instruments it is essential for accurate work. For instruments of this class, air damping is most satisfactory. In Fig. 61*a* the piston (*p*) moves through the curved cylinder with a small amount of clearance, and the fact that the air has to leak past the piston, prevents sudden movements of the system.

There is a large number of instruments of the moving iron type made, but their chief use is for alternating currents, measurements, and they are only used in C.C. circuits, when cheapness is a consideration. The reason is, that however carefully they are designed, they are subject to an error when used on C.C. circuits. We shall explain how this error arises by referring to the repelled iron type, but the error is common to all moving iron instruments.

In chapter ii. it was mentioned that iron retains a certain amount of magnetism after the magnetising force is removed. The percentage of magnetism retained, varies with the kind of iron, and as a general rule, the harder the brand, the larger is the fraction retained. But the softest and purest iron exhibits the property to which the term *hysteresis* has been applied. Now the two plates of iron in the instrument under discussion are magnetised by the action of the current, and the deflection of the pointer is determined by the amount of magnetism produced. The strength of pole produced in these plates will be greater for a given current flowing round the coil when the current has been reduced from a higher value, than when it has been increased to the value in question. Consequently, these instruments will read higher with decreasing than with increasing currents. Fig. 63 shows the difference between the readings for increasing and decreasing current with an ammeter of this class. For measuring alternating currents, the pointer takes up an intermediate position, and the hysteresis does not effect the accuracy.

Voltmeters of the moving iron type have coils wound with

copper wire, and a resistance coil of manganin or eureka wire is connected in series with the solenoid. The resistance of the copper coil changes about .4 per cent. for a change of 1° C, but the value of the series resistance is practically independent of temperature. If, therefore, the resistance of



RELATION BETWEEN CURRENT AND READING ON MOVING IRON AMMETER.

Lower curve—current increasing.
Upper curve—current decreasing.

the copper coil is a small fraction, for instance, $\frac{1}{10}$ of the total resistance of the circuit, the temperature error will be negligible. In the case of ammeters, the coil is often wound with bare strip bent edgewise, the adjacent turns being kept apart by the rigidity of the material.

Moving Coil Instruments.—This is the most important class of instruments used for measurements in continuous current

work. When a coil carrying a current is placed in a magnetic field, it will tend to move into such a position that the plane of the coil is at right angles to the field. When the lines of the field are parallel, the torque produced will depend on the angle which the coil makes with the field, but in the case of instruments, it is arranged that the magnetic field is radial

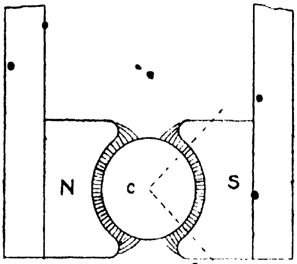


FIG. 64*a*. DISTRIBUTION OF FIELD IN MOVING COIL INSTRUMENT.

so that the strength of the field in which the coil moves i practically constant. Fig. 64*a* will illustrate this. C is a soft iron core, and the poles of the permanent magnet ar bored out concentric with this core. Hence, over an angl of 90°, the magnetic field will be practically uniform. Th

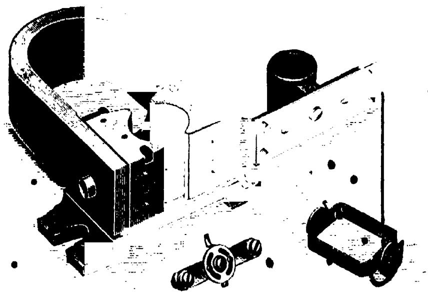


Fig. 64*b*. PARTS OF MOVING COIL INSTRUMENT BY NALDER BROS.

core C is sometimes made spherical, but generally cylin drical. Fig. 64*b* shows the parts of an instrument manufac tured by Messrs Nalder Bros.

The permanent magnet is about 6 inches long, and has a cross-section of $1\frac{3}{8}'' \times \frac{3}{8}''$. The diameter of the soft iron cor situated between the poles is 1 inch, and the length of th

gap is about $\frac{1}{8}$ inch. The coil is wound with silk-covered copper wire wound on a former made of copper. The gauge of the wire on the coil depends on the use to which the instrument is to be put; for an ammeter it would be larger than for a voltmeter, and the coil would, of course, consist of fewer turns. This coil is mounted in pivots working in jewelled centres, and the current is led in and out by two hair springs made of phosphor bronze. These springs also serve as the control, and are wound in opposite directions to reduce the effect of change of temperature. The position of one of the springs may be adjusted to alter the zero.

Attached to the coil is a light pointer made of aluminium tube. This pointer is balanced by means of small counter weights, and the end is flattened out and moves over a scale

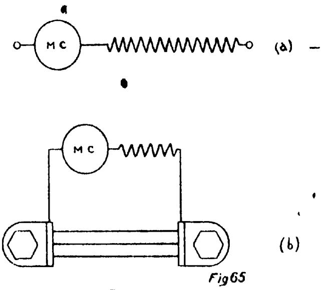


Fig. 65. ARRANGEMENT OF CIRCUITS IN MOVING COIL INSTRUMENTS.

which is graduated. Instruments which are to be read very carefully are provided with a mirror so that the eye may be placed in such a position that the pointer covers its image in the mirror, thus avoiding parallax. The metal former acts as a damping device, because when the coil moves, a current flows round it, and this causes the motion to be arrested. This is a very satisfactory way of making an instrument dead beat.

If the magnetic field in which the coil moves were quite uniform, and the torque exerted by the springs exactly proportional to the angle of deflection, the deflection would be strictly proportional to the current passing round the coil, and the graduations would be equal. For switchboard purposes, this proportionality is sufficiently accurate, and printed uniform scales are sometimes used, but for standard instruments the scales are calibrated at various points.

The connections for moving coil instruments are shown in Fig. 65 in which (*a*) refers to a voltmeter, and (*b*) to an ammeter. In the case of a voltmeter, the resistance of the moving coil

(copper) is so small compared with the total resistance from terminal to terminal, that the temperature error is negligible except in very low reading instruments. With ammeters this is not the case, and if much resistance is inserted a large drop is required across the shunt.

It has become customary, and this is the recommendation of the engineering standards committee, to allow a drop of 0.075 volt for the shunts in moving coil ammeters. It is important always to connect an instrument to its shunt with the leads with which the instrument was calibrated; if longer or thinner leads are used, the indications will be too low.

Recording Instruments.—For continuous current measurements, the moving coil principle is generally adopted. At the end of the pointer is a special kind of pen capable of holding a considerable quantity of ink. This pen moves over a drum which is slowly rotated by clockwork about an axis at right angles to the axis of rotation of the movement. This will be clear from Fig. 66*a*. Upon the metal drum is fixed a paper chart, and this is ruled with a time scale in one direction and a scale of amperes or volts in the other. Now when the drum is rotated, a continuous line will be produced by the pen. This will be at a constant distance from the zero line if the deflection of the pointer is constant, but will show varying heights when the deflection changes. Thus the instrument may be made to draw a graph, and a permanent record of voltage or current is obtained.

The movement is similar to that of a non-recording instrument, but is usually rather larger, and the forces at work bigger, on account of the friction between the pen and the paper.

Recording instruments are chiefly used in generating stations to show the engineer how the load has varied during the day, and also to show the variation of the voltage. It is interesting to notice, although the subject cannot be entered into here, that any quantity such as temperature, the measurement of which may be reduced to the measurement of a current, may be recorded by means of an apparatus of this kind.

Fig. 66*b* is reproduced from a portion of the chart taken from one of the recording instruments described. By a special arrangement the pen is constrained to move always parallel to the axis of rotation of the paper, and therefore the record is obtained plotted on rectangular co-ordinates.

Integrating or Service Meters.—Two kinds of meters of this class must be distinguished, viz.:—

(*a*) Ampere-hour meters.
(*b*) Watt-hour meters.

The indication of an instrument of class (*a*) is really a measure of the quantity of electricity which has passed round a circuit, but since

$$\underset{\text{(watt-hours)}}{\text{energy}} = \underset{\text{(ampere-hours)}}{\text{quantity}} \times \underset{\text{(volts)}}{\text{E.M.F.}}$$

it follows that if the pressure of a circuit be constant, the energy which has been supplied to it may be measured by the number

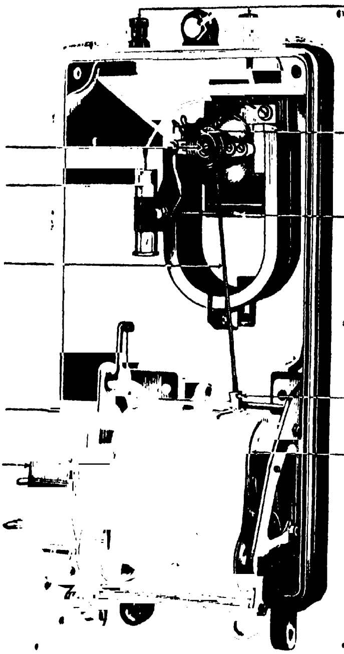


Fig. 66*a*. General View of Moving Coil Recorder by Evershed & Vignoles.

of ampere-hours which has passed. For this reason, ampere-hour meters are always calibrated to read in kilowatt-hours directly, and give a true indication of the energy supplied, provided that the pressure has been equal to that for which the meter was intended. Moreover, an ampere-hour meter may be used on any circuit, provided that the readings obtained are multiplied by the ratio of the pressure of the circuit on

which the meter was used, to the pressure for which it was designed.

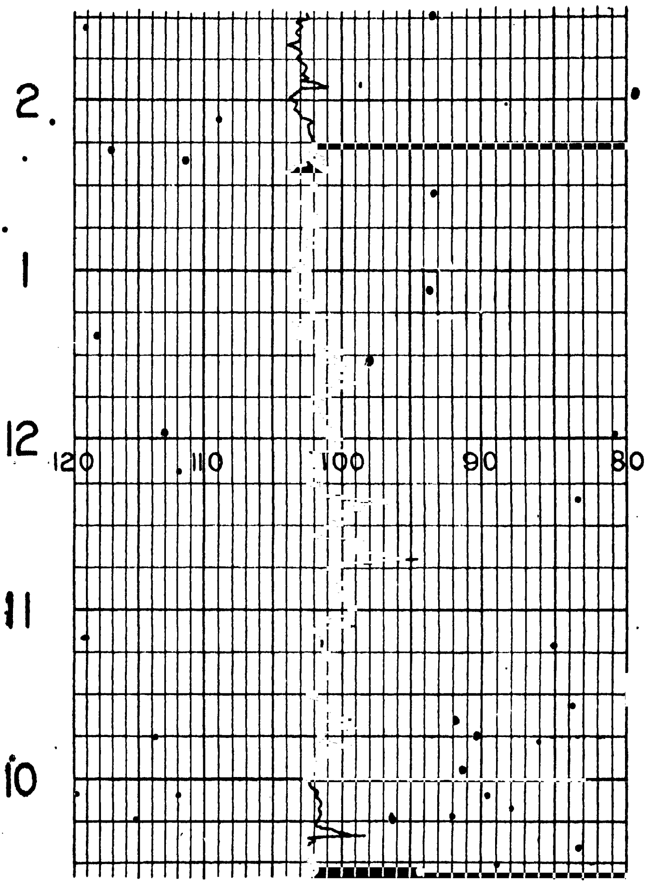


Fig. 66b. SPECIMEN OF CHART RECORD OBTAINED WITH EVERSHED RECORDING AMMETER.

Electrolytic Meters.—The amount of chemical action whic takes place in a circuit is proportional to the quantity of electricity which has passed round the circuit. For instance, the amount of copper deposited on a copper plate from a solution

of a copper salt is proportional to the number of ampere-hours. When we desire to measure the quantity of electricity, this principle seems at first sight the most suitable one to adopt. At the present time, however, although there has been a large number of very ingenious meters of this class brought out, and there are some good ones on the market, the type is not very much in favour with engineers. There are many reasons

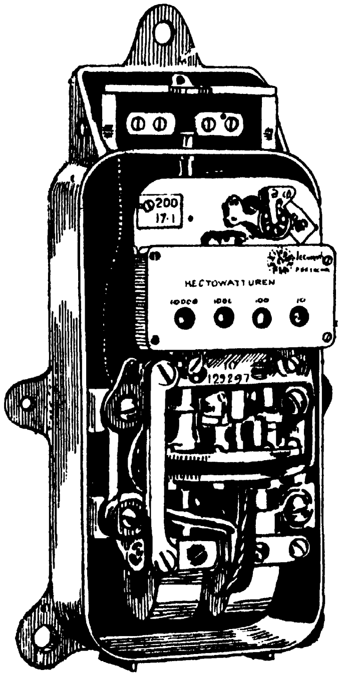


Fig 67.

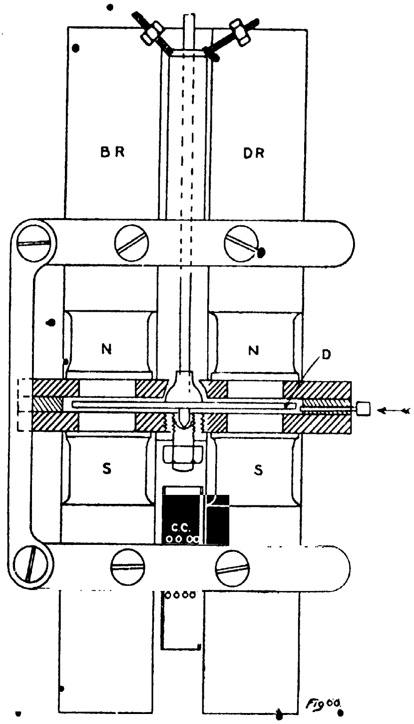
General View of Ferranti Ampere-Hour Meter.

for this, the chief being the difficulty and cost of repair and the destruction of the record after the meter is "read."

Mercury Motor Meters.—Most of the ampere-hour meters at present in use belong to this type. The Ferranti meter described below is a good example of this class, and enormous numbers are turned out every year. Fig. 67 shows the appearance of the meter, and Fig. 68 is intended to explain the mode of action. The disc D is of copper and floats in mercury which

is contained in the insulating chamber. The current passing through the meter is led into this disc at the right-hand side and passes out near the spindle upon which the disc is mounted. This vertical spindle is mounted in jewels and is geared to a train of wheels which cause revolution of the pointers.

Two permanent magnets, known as the driving and brake magnets respectively, are mounted so as to produce a field



DIAGRAMMATIC VIEW OF FERRANTI AMPERE-HOUR METER.

across the copper disc. These magnets are shaped like a letter C inverted. Assume that the current passes across the disc from right to left, and that the magnetic field has an upward direction across the disc. Then applying the left hand rule, it will be found that the disc will revolve from left to right at the front, or in an anti-clockwise direction looking from the top. Thus the disc is driven at the right hand side with a force which, supposing the field to be constant, is proportional

to the current passing. On the left hand side there is a conductor moving through a magnetic field at right angles to the flux; hence eddy currents are produced and these retard the motion. This braking action, however, must take place on both sides. Now the E.M.F. generated in a moving conductor is proportional to the speed, and unless the temperature changes, the current produced is proportional to the E.M.F. The retarding torque is proportional to the eddy currents in the disc, and hence the braking action is proportional to the speed. When the meter is running at constant speed, the driving torque must equal the retarding torque, therefore

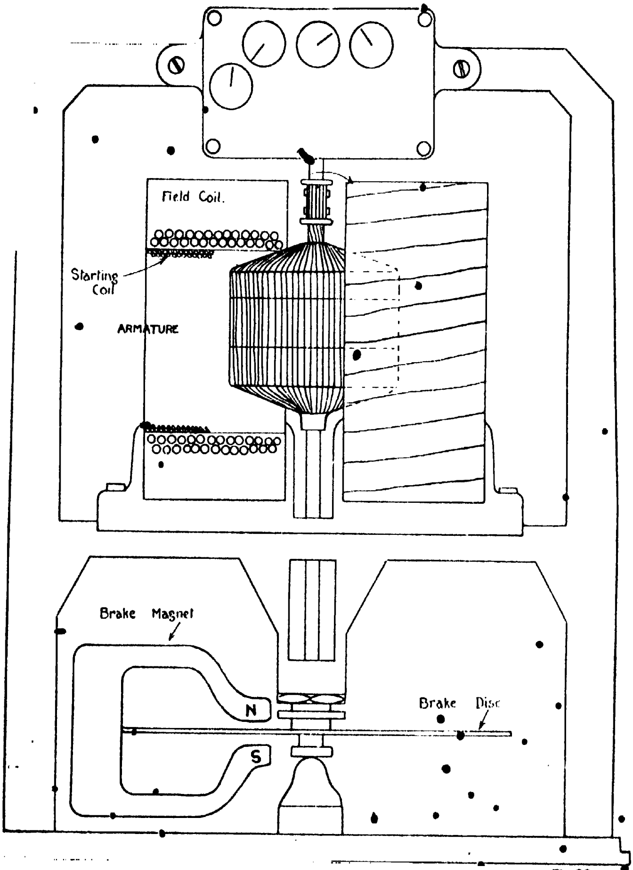
$$\begin{aligned} \text{speed} &\propto \text{driving torque} \\ &\propto \text{current} \end{aligned}$$

and as a consequence, number of revolutions $\propto$ current $\times$ time
$\propto$ quantity.

Thus apart from the disturbing effects of friction, the number of revolutions of the disc, and therefore the indication of the pointers, is a measure of ampere-hours. The coil (CC) shown in Fig. 68 is wound on a soft iron core. The object of this is to reduce the error which would otherwise be caused by the large fluid friction at high speed. The coil in question contains a few turns and carries the same current as the disc. A magnetic field is set up by it, which increases the driving magnet flux, and reduces the flux in the gap of the brake magnet. Hence, at high speeds, the torque per ampere is increased, and the brake torque on the left-hand side reduced. This compensates for the increased friction between the disc and the mercury. Meters for large currents (above 50 amperes) are provided with shunts. A mercury motor meter, in common with all apparatus containing permanent magnets, suffers from the liability of the magnets to be weakened. In this case, the effect is not serious unless the demagnetisation is very large, because a 1 per cent. diminution in the strength of the magnets will reduce both the driving and the retarding torques in the same proportion, and the error caused will be much less than 1 per cent.

Watt-Hour Meters.—Watt-hour meters differ in principle from those described, in that the accuracy of the meter does not depend on the constancy of the pressure. The chief application of watt-hour meters is to alternating current measurements, but there are some station engineers who prefer this type for C.C. circuits. Compared with ampere-hour meters, their main disadvantages are their slightly higher cost (in the case of meters for small currents) and the loss which continuously takes place in the shunt circuit.

One of the best known examples is the original Thomson motor meter, and it is a meter of this pattern which is described below. Such a meter may be used on either con-



ARRANGEMENT OF THOMSON WATT-HOUR METER.

tinuous or alternating current circuits. The Thomson watt-hour meter, manufactured by the British Thomson Houston Co., is very similar to a C.C. motor. A sketch to explain the action of this meter is shown in Fig. 69, and a general view is shown in Fig. 70. The armature (*a*) is wound with

fine copper wire, and the coils are connected to a small commutator. Light springs press on this commutator and lead the current in and out. The armature itself has a high resistance,

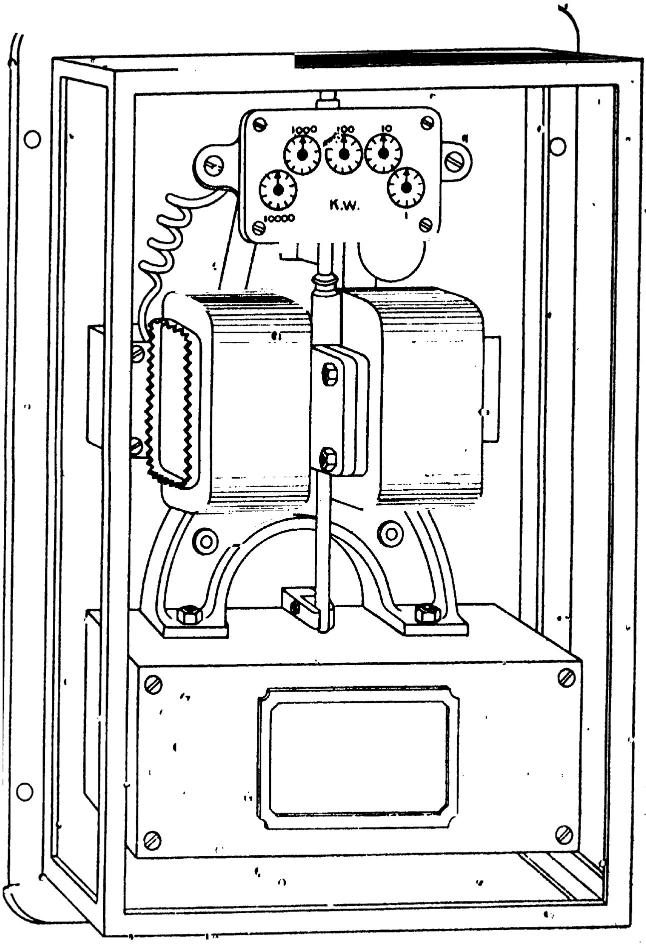


Fig. 70.

GENERAL VIEW OF THOMSON WATT-HOUR METER (SWITCHBOARD PATTERN).

and is connected in series with coils of wire of some resistance alloy wound non-inductively. The resistance of the armature circuits depends upon the voltage for which the meter is intended, but the current passing through the armature is of the order of $\frac{1}{30}$ ampere. The armature is supported by a vertical spindle which is mounted between jewelled centres, and at the upper end is a worm. This engages with a worm wheel, and is geared with the "fingers" on the dials. On either side of the armature is a "field" coil wound with wire capable of carrying the full load current. For this reason they are known as series coils. This coil produces a magnetic field in the armature, and as a consequence, the current in the armature causes it to rotate. Unlike an ordinary motor, there is no iron in the magnetic circuit, and the flux is proportional to the current in the series coils. In addition, there is a fine wire coil mounted coaxially with the series coils and connected in series with the armature. This coil produces a magnetic field in the same direction as the series coils, and enables the meter to start with a smaller current in the main coils than would otherwise be required. It is known as a "starting coil." Finally, there is mounted upon the armature spindle, a disc of copper (*d*), which revolves between the poles of one or more permanent magnets, the arrangement forming a brake. The action of this brake has already been described in connection with the Ferranti ampere-hour meter. The torque upon the armature depends, as in an ordinary motor, upon the armature current and the field strength, *i.e.*, $T \propto C_a \times C_f$.

But $C_a \propto$ voltage and $C_f =$ total current in main circuit,

therefore
$$\begin{aligned} T &\propto C_a \times C_f \\ &\propto \text{voltage} \times \text{current} \\ &\propto \text{watts}. \end{aligned}$$

As explained on p. 140, speed $\propto$ driving torque.

therefore
$$\text{speed} \propto \text{watts}.$$

The friction of the meter and the train would cause the speed to be too low for small currents, and the starting coil partially compensates for this by producing a torque when there is no main current. This starting coil is so adjusted that a very small current in the series coils will be sufficient to overcome the standing friction. It is often found that if tapped, a meter of this type will run on the shunt circuit alone.

EXAMPLES

(1) Describe any moving coil ammeter with which you are acquainted. What advantages has this type over soft iron and hot wire instruments? (C & G).

(2) What is the difference between an energy meter and a coulomb meter Describe in detail, with sketches, some form of ampere-hour meter.

(3) The resistance of the movement of a moving coil instrument is 10 ohms and full-scale deflection is produced by a current of 0.01 ampere. Calculate the value of the series resistance which must be used to make the instrument give full-scale deflection with 150 volts. What length of No. 40 Eureka wire (40 ohms per yard) will be required for the series resistance?

(4) Give descriptions of two types of moving iron instruments. Why is this class of instrument not generally used on C.C. circuits?

(5) How does a voltmeter differ from an ammeter in its construction and use? What sort of a resistance may be given to a voltmeter used with a single accumulator? (C & G) (E).

(6) Describe the Thomson energy meter, and show that the number of revolutions is proportional to the energy used.

(7) Describe with sketches the construction of a moving-coil amperemeter, and mention the advantages and disadvantages of this kind of instrument as compared with other common types. (C & G) (E).

(8) A certain C.C. amperemeter has a resistance of 0.01 ohm and may be used for measuring currents up to 2 amperes. Explain how the range of readings may be extended by the use of a shunt, and give the resistance of the shunt that would enable currents to be measured up to 20 amperes. (C & G) (E).

(9) What are the essential features of a good house meter? Describe the Thomson energy meter, and show that the number of revolutions is proportional to the energy used. Why is it incorrect to call this instrument a recording wattmeter? (C & G) (O).

(10) Describe in detail with sketches a soft iron voltmeter suitable for measuring either direct or alternating pressures, and point out the errors usually met with in such instruments when used on C.C. circuits. (C & G) (O).

(11) Under what conditions is it permissible to determine by means of the indications of an ampere-hour meter the money value of electrical energy supplied to a consumer? Why do the managers of C.C. central stations generally prefer such meters to watt-hour meters? (C & G) (E).

(12) Define the terms "one joule," "one kilowatt-hour," "one Board of Trade unit." The price of electrical energy in a certain town is 4d. per B.O.T. unit, and the supply pressure is 200 volts. An electricity energy meter on this circuit has a resistance of 10,000 ohms in its pressure coil; calculate the cost of the energy wasted in this coil in a quarter of a year. (C & G) (E).

(13) The flux density in the air gap of a moving coil instrument is 1000 lines per square centimetre. The moving coil consists of 15 turns and is wound on a former 3 centimetres by 2 centimetres. Calculate the torque produced when a current of $\frac{1}{10}$ ampere passes round the coil.

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